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The Neogene Stratigraphic Scale of the Eastern Paratethys

L. A. Nevesskaya*, I. A. Goncharova*, L. B. Il'ina*, N. P. Paramonova*, and S. O. Khondkarian**

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Abstract—The Neogene stratigraphic scale comprising 12 regional stages of the Eastern Paratethys is discussed. The stratotype, its lithology, and characteristic micro- and macrofossils are given for every regional stage with indication of their stratigraphic position and probable correlation with regional stages of the Western Paratethys and with stages of the Mediterranean scale. Paleogeographic features of the Eastern Paratethys and its links with other basins are characterized for every stage of the Neogene history. A particular attention is paid to boundaries of series and subseries. The lower Neogene boundary is arbitrarily drawn in the lower part of the Caucasian regional stage, the lower–middle Miocene boundary is drawn within the Tarkhanian regional stage, and the middle–upper Miocene boundary is placed within the uppermost middle Sarmatian regional stage. The Miocene–Pliocene boundary coincides with the top of the Pontian regional stage whereas the Neogene–Quaternary boundary is placed slightly above the upper boundary of the Akchagylian regional stage.

Key words: Paratethys, stratigraphy, paleogeography, regional stages, fauna, flora.

The Neogene stratigraphic scale of the Eastern Paratethys represents the thoroughly traced succession of regional stages. Accordingly, it can be used to reconstruct the entire Neogene history of this spacious basin.

The elaboration history of the Pontian–Caspian (Eastern Paratethys) Neogene stratigraphic scale lasted longer than a century. The first step in its elaboration is connected with the name of Barbot de Marny, and the first version was proposed by N.I. Andrusov who defined most of current regional stages (=horizons). The lower part of the scale was extended later on by L.Sh. Davitashvili, and the lowermost regional stage (Caucasian) was defined by A.K. Bogdanovich, M.V. Muratov, M.F. Nosovskii, and L.S. Ter-Grigor'yants.

This regional stage scale was adopted at the 6th Congress of the Regional Committee on Stratigraphy of the Mediterranean Neogene (RCSMN) in 1975 (*Trudy 6-go Kongressa...*, 1976) and by the Bureau of the Interdepartmental Stratigraphic Committee of the USSR in 1983. It was published in 1984 in the periodical *Sovetskaya geologiya* (Nevesskaya *et al.*, 1984) and in the volume *Neogenovaya sistema...* (1986). Paleontological characteristics were outlined for all regional stages. Bivalve mollusks were considered as an orthostratigraphic group, although other benthic organisms (gastropods, foraminifers, ostracodes) and mammals were indicated as well. The regional stages were correlated with the Mediterranean standard and with regional stages of Central Europe (Western Paratethys).

The study of the Neogene stratigraphy in southern Russia and adjacent countries was in progress after publication of the volume *Neogenovaya sistema...* (1986). It included a thorough analysis of mollusks and their evolution in response to changes in different-type basins of the Pontian–Caspian region during the Neogene (Nevesskaya *et al.*, 1986, 1993, 1997; Goncharova, 1989; Il'ina, 1993; Popov *et al.*, 1993; Paramonova, 1994; Danukalova, 1996). In addition to materials available by that time (Semenenko and Lyul'eva, 1978), new data on nannofossils were obtained (Minashvili, 1986; Semenenko, 1987; Muzylev and Golovina, 1987; Bogdanovich and Ivanova, 1997; Golovina, 1998; Mărunteanu, 1998; Mărunteanu *et al.*, 1998, 2000; Andreeva-Grigorovich and Savytskaya, 2000). They improved correlation of regional stages of the Eastern Paratethys with stratigraphic units of the Mediterranean region and Western Paratethys. Dinoflagellates initially investigated by (Andreeva-Grigorovich, 1980) were also under keen attention in last decades (Akhmetiev *et al.*, 1995; Akhmet'ev and Zaporozhets, 1996; Zaporozhets, 1998, 1999, Filippova, 1998, 2002).

The subsequent study of Neogene reference sections, including that of the Krasnodar super-deep well SD-12000 that penetrated the entire Neogene (5000 m) and was completely cored, and of natural exposures was carried out in collaboration with geologists from the Federal State Unitary Enterprise *Kavkazgeols'emka*. Among the latter, there were exposures of the Belaya River (lower Miocene–Pliocene), Taman Peninsula (middle Miocene–Pliocene), and many outcrops in the Western Ciscaucasia. All the data obtained contributed much to further perfection of the scale under consideration.

Stages in development of Neogene basins and their biotas, which were first established by N.I. Andrusov, represented a basis for defining regional stratigraphic units (regional stages or horizons) of the Neogene scale of the Eastern Paratethys. The basin history was of a cyclic transgressive–regressive character, and regional stages distinguishable in the shallow-water zone of the basin are frequently separated therefore by stratigraphic hiatuses and unconformities. Along with distinct biotic changes, regional unconformities are suitable for a reliable definition of boundaries between regional stages, which are traceable throughout the Eastern Paratethys from northeastern Bulgaria and, sometimes, eastern Serbia to the Aral and Kopetdag regions. Southern parts of the Western Kuban' and Terek–Caspian troughs and the Kobystan–South Caspian depression represent exceptions.

The Neogene stratigraphic scale of the Eastern Paratethys includes 12 regional stages, of which the Caucasian (its greater part), Sakaraulian, Kotsakhurian, and lower Tarkhanian are referred to the lower Miocene, while the upper Tarkhanian, Chokrakian, Karaganian, Konkian, and lower–middle (main part) Sarmatian are included into the middle Miocene. Then there are upper middle and upper Sarmatian, Maeotian, and Pontian stages of the upper Miocene, the Kimmerian Stage of the lower Pliocene, and the Akchagylian Stage of the middle–upper Pliocene (Table).

In comparison with the previous Eastern Paratethys Neogene scale (Nevesskaya *et al.*, 1984, 1986), the following modifications are characteristic of the scheme presented in this work. The Tarkhanian regional stage is referred partly to the lower Miocene and partly to the middle Miocene. The Pontian earlier considered a Pliocene subdivision is included into the upper Miocene. The Kimmerian is transferred from the middle into the lower Pliocene, and the Akchagylian, the uppermost regional stage of the Neogene, corresponds to the middle–upper Pliocene in accord with the new scale of the Mediterranean Pliocene that is subdivided into three subseries and includes the additional Gelasian Stage. Inasmuch as the lower boundary of the Quaternary System is accepted to be at the level of 1.81 Ma (Resolution of the Interdepartmental Stratigraphic Committee of January 30, 1998), the Apsheronian regional stage regarded previously as the upper Pliocene unit is placed into the Quaternary.

THE NEOGENE LOWER BOUNDARY

According to decisions of the 6th Congress of the Regional Committee on Stratigraphy of the Mediterranean Neogene (*Trudy 6-go Kongressa...*, 1976; Steininger and Rögl, 1983), the Neogene lower boundary corresponds to the base of the Aquitanian.

Faunal assemblages cross the Paleogene–Neogene boundary without considerable changes in composition. In planktonic foraminifer zonation, the boundary is placed at the base of either the N4 (Blow, 1969) or M1 zones (Berggren *et al.*, 1983) and corresponds to the base of the NN1 Zone of nannoplankton scale (Berggren *et al.*, 1995).

Inasmuch as the lower boundary of the Aquitanian Stage and its relationship with underlying Upper Oligocene strata are unclear in the its stratotype area (southwestern France, Aquitaine basin), the Working group on the Paleogene–Neogene boundary selected, after lengthy (since 1976) investigations of many sections in Italy, Greece, and Romania, the Lemme-Carrosio section in the Piedmont basin of northwestern Italy for the boundary stratotype (Steininger, 1992).

This section is located east of the Carrosio Village at the right bank of the Lemme River, where it is represented by siltstones of the upper Oligocene–lower Miocene Rigoroso Formation more than 60 m thick. The section is composed of massive obscurely bedded siltstones (Members A and B_1) in the lower part. Higher in section, there are alternating massive and bedded siltstones (Member B_2 and lower part of Member B_3), and then largely thin-laminated siltstones (upper part of Member B_3), and mostly massive siltstones (Member A) constitute the topmost part.

These sediments accumulated in an upper bathyal setting yield calcareous nannofossils, planktonic and benthic foraminifers, and dinoflagellate cysts.

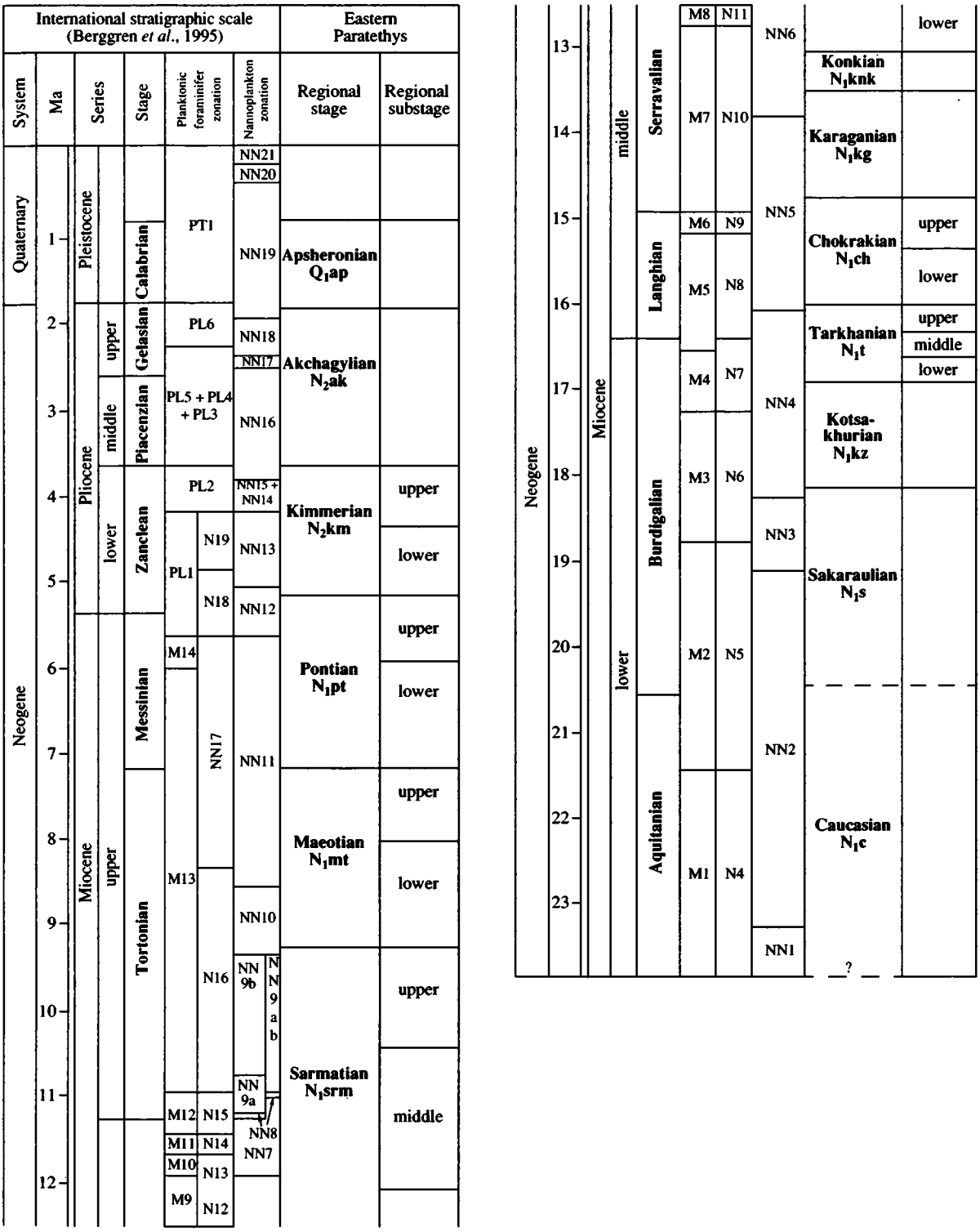
The Paleogene–Neogene boundary in this section is distinguished within the Member B_2: 2 m above its base and 35 m below the section top.

The boundary is defined based on the following biostratigraphic markers. *Calcareous nannoplankton*: FAD of *Sphenolithus delphix* 12 m below the boundary, i.e., below the 35-m mark, and its LAD 4 m higher; FAD and LAD of *Sphenolithus capricornutus* within the 1-m-thick interval above the 35-m mark. *Planktonic foraminifers*: FAD of *Paragloborotalia kugleri* 2 m above the 35-m mark and its LAD 25 higher, FAD of *Globoquadrina dehiscens* 12 m higher and FAD of *Globigerinoides altiapertutus* 22 m higher. *Benthic foraminifers*: FAD of *Uvigerina spinicostata* 1 m above the 35-m mark and its LAD 21 m higher. *Dinoflagellate cysts*: FAD of *Ectosphaeropsis burdigalensis* 3 m below the 35-mark; last abundance level of *Chiropteridium* spp. 4 m below and their LAD approximately 1 m above the boundary; explosive abundance of *Deflandrea* spp. about 10 m above the 35-m mark and last finds of the genus 20 m higher; FAD of *Distatodinium apenninicum* 25 m above the boundary; FAD of *Membraninarlacia picena* 32 m higher, and FAD of *Stoveracysta conerae* 34 m higher.

According to *magnetostratigraphic data*, the Paleogene–Neogene boundary is localized between Subchrons C6Cn2r and C6Cn2n at the level corresponding to the age mark of 23.8 Ma (Cande and Kent, 1992).

Isotopic chemostratigraphy revealed increased ^{18}O values within the interval from the 35-m mark to 13 m and higher. This excursion corresponds to the event Mi-

Correlation chart of Neogene regional stages of the Eastern Paratethys with the International stratigraphic scale



1 (Miller *et al.*, 1991) and is correlative with Chron C6Cn that is 23.5 Ma old.

Thus, the Neogene lower boundary corresponds in the stratigraphic section under consideration approximately to the base of the NN1 Zone (Martini, 1971) and to the base of the CN1A Subzone (Bukry, 1973) in the nannoplankton zonation. Being also correlative with the base of *Paragloborotalia kugleri* (Bolli, 1957) or M1 zones (Berggren *et al.*, 1985), it is simultaneously close to the base of the *Globoquadrina dehiscens* Sub-

zone (Iaccarino and Salvatorini, 1982) in the foraminiferal zonation. In the magnetostratigraphic record, it coincides with the boundary between Subchrons C6Cn2r and C6Cn2n that is 23.8 Ma old (Steininger *et al.*, 1994).

In the Eastern Paratethys, the boundary in question is arbitrarily drawn in the lower part of the Caucasian regional stage and its analogues (probable counterparts of the Aquitanian Stage).

CAUCASIAN REGIONAL STAGE

The Caucasian regional stage (?upper Oligocene–lower Miocene) was defined by A.K. Bogdanovich, M.V. Muratov, M.F. Nosovskii, and L.S. Ter-Grigor'yants (Nevesskaya *et al.*, 1975). Its stratotype described in several works (Prokopov, 1937; Ter-Grigor'yants, 1969; *Neogenovaya sistema...*, 1986) is located near the town of Cherkessk at the Kuban' River (central Ciscaucasia). The Caucasian regional stage of this section corresponds to a middle part of the Maikop Group spanning intervals of the Alkun and Zelenchuk formations (with Septarian Beds at the base) and the lower part of the Karadzhalga Formation (Nevesskaya *et al.*, 1975; Nosovskii and Bogdanovich, 1980; *Neogenovaya sistema...*, 1986). The lower boundary of the stage is defined here within the clay sequence of a uniform lithology at the level, above which the impoverished microfauna of the underlying upper Oligocene Batalpashinsk Formation is replaced by a more diverse assemblage of polyhaline benthic foraminifers (*Virgulinella neobuliminoides, Bolivina* ex gr. *plicatella*, and others), which are characteristic of the Alkun Formation composed of non- to slightly calcareous clays enclosing marl and limestone lentils. The Alkun Formation yields nannofossils of the NP25 (Andreeva-Grigorovich, 1977) or NP25–NN1 (according to E. Martini, in Nosovskii and Bogdanovich, 1980) zones. The overlying Zelenchuk Formation consists of non-calcareous silty clays with sandstone interbeds. This formation encloses abundant septarian nodules in its lower part (Septarian Beds), while clays yield scarce agglutinated foraminifers *Ammodiscus* and *Haplophragmoides*. The overlying Karadzhalga Formation is of a similar composition (clays with siderite nodules). Its lower part is referred to the Caucasian Stage, whereas the upper one that yields polyhaline foraminifers, pteropods, and radiolarians, is attributed to the overlying Sakaraulian regional stage (Nosovskii and Bogdanovich, 1980; *Neogenovaya sistema...*, 1986). The total thickness of the Caucasian regional stage in the stratotype is 155 m (Nosovskii and Bogdanovich, 1980).

Buryak and Bogdanovich (*Neogenovaya sistema...*, 1986) regarded the borehole section Derbetovskaya 37 drilled at the northeastern slope of the Stavropol' uplift (platform area of the western Ciscaucasia) as a stage parastratotype, in which the Caucasian Stage is composed, like in the stratotype, of the Maikop clays. The stage lower boundary coincides in this section with the boundary between beds with the extrinsic microfauna (analogues of the Batalpashinsk Formation in the stratotype) and overlying strata with *Bolivina goudkoffi* and associated *Uvigerinella californica, Porosononion dendriticus*, and others. The latter are overlain in turn by beds with *Uvigerinella californica*, which crown the stage. Higher in the section, there are beds with *Neobulimina elongata* of the Sakaraulian regional stage. The Caucasian deposits are 145 m thick in the parastratotype (Nosovskii and Bogdanovich, 1980).

The Caucasian regional stage is subdivided into the lower and upper substages with the boundary between them coinciding with that between beds with *Bolivina goudkoffi* and *Uvigerinella californica* (Nevesskaya *et al.*, 1975; Nosovskii and Bogdanovich, 1980). In the stratotype area, the lower substage spans the interval of the Alkun Formation coupled with the lower part of the Zelenchuk Formation, whereas the upper substage corresponds to the upper part of the latter and overlying lower part of the Karadzhalga Formation (Nosovskii and Bogdanovich, 1980; *Neogenovaya sistema...*, 1986).

According to the aforementioned nannofossil record (although controversial), the Caucasian regional stage can be correlated with the Aquitanian Stage of the Mediterranean scale or with the Egerian regional stage of the Western Paratethys.

The stratigraphic position of the Caucasian is still debatable. In the Neogene scale of the Eastern Paratethys (southern areas of the former Soviet Union and some East European countries), it is referred to the lower Miocene and correlated with the Aquitanian Stage of the Mediterranean stratigraphic scale and with the upper part of the Egerian regional stage of the Western Paratethys (*Trudy 6-go Kongressa...*, 1976; Nevesskaya *et al.*, 1975, 1984; *Neogenovaya sistema...*, 1986).

Nevertheless, there are alternative standpoints. For instance, Popov *et al.* (1993a) referred the lower part of the Caucasian (Alkun and Zelenchuk formations) to the Oligocene in contrast to the Karadzhalga Formation correlated with the Miocene and considered as an autonomous regional stage with stratotype at the eponymous river (western Ciscaucasia region) and with hypostratotype at the Kuban' River near Cherkessk. In their opinion, the lower Caucasian strata should be regarded as an independent Kalmykian regional stage correlative with the upper Chattian. These researchers did not substantiate properly the introduction of Kalmykian and Karadzhalganian regional stages instead of the Caucasian Stage and even did not mention the last name in their work. Such an approach seems strange and not quite correct, particularly if we take into consideration that the Egerian regional stage of the Western Paratethys, a possible equivalent of the Caucasian Stage, is also of a debatable status: the basal and upper Egerian strata are referred to the upper Oli-

gocene and lower Miocene, respectively, but it is anonymously considered as a valid stratigraphic unit. In any case, the problem of stratigraphic position of the Caucasian regional stage still waits its solution and cannot be avoided by simple introduction of new regional stages.

It is also difficult to define analogues of the Caucasian in other regions of the Eastern Paratethys. Based on the results of recent collective study, it can be assumed as correlative with the following subdivisions: (1) the Askaniya (upper part) and Gornostaevka formations of the northern Black Sea region, (2) the upper Kerleut Subformation of the Crimea, (3) the Sivash Beds of the Dnieper–Donets depression, (4) the middle subgroup of the Maikop Group including the Nugra Formation of the Volga–Don interfluve, (5) the upper lower and upper Uplistsikhe subformations of Georgia, (6) the Karagiin (upper part) and Kashkaraty (lower part) formations of Mangyshlak, (7) the Karatomak (upper part) and Baigubek formations of northern Ustyurt, the Aral Formation and Kintykche Beds included, (8) the Chagrai (upper part) and Aral (middle part) formations of the eastern Aral region and the upper Sarbatyr Subformation of Kyzylkum (entirely or partly), (9) the uppermost part of the Kyzylcha Formation of southeastern Turkmenistan, and (10) the Gissarskii Beds of Tajikistan (*Neogenovaya sistema...*, 1986; Goncharova and Popov, 1990; Popov *et al.*, 1993a, b; Goncharova and Popov, 1995; Nosovskii, 1998a, b).

The Caucasian basin was a part of the Paratethys, which stretched in latitudinal direction from southern areas of Europe to the northern Aral region. Marginal areas of the basin accumulated shallow-water sandy sediments, and characteristic of its deeper zones (the Ciscaucasia region and Terek–Caspian trough) was mud enriched in unaltered organic matter, probably deposited in H_2S-contaminated settings, and bearing abundant fish remains. The molluscan assemblages from shallow areas includes representatives of *Glycymeris, Cubitostrea, Glossus, Arctica, Gibbolucina, Venus, Callista*, and *Nemocardium* genera accompanied by taxa untypical of subsequent basins (*Palliolum* s. str. and *Lentipecten*). Deeper zones were populated by *Thyasira, Cuspidaria, Nuculana, Palliolum (Delectopecten)*, and others. Characteristic of the Trans-Caucasian basin areas were thermophilic genera *Arca, Barbatia, Isognomon, Cardita* s. str., and others. Salinity in open areas of the basin was about 30‰ and decreased to 15–20‰ in its northeastern part and coastal areas influenced by the river runoff. Prevalent in these areas were euryhaline bivalves *Cerastoderma prigorovskii* and *Corbula helmerseni.*

The Caucasian basin was mostly warm, though its northern areas were colder than the southern ones, particularly than the Trans-Caucasian part populated by thermophilic molluscan genera. Connections between the Paratethys and basins of northwestern Europe were either closed or very restricted at that time (Popov *et al.*, 1993a).

SAKARAULIAN REGIONAL STAGE

The Sakaraulian regional stage (lower Miocene) was originally distinguished by Davitashvili (1933). Its stratotype located in the Sakaraul'skaya Ravine opposite the town of Kaspi (eastern Georgia) was defined but not described by G.D. Kharatishvili.

Latter on (*Stratotipy yarusov...*, 1975), the section described near the Metekhi Village (Kvaliashvili, 1970; Voronina *et al.*, 1991) was selected to represent a hypostratotype of the regional stage in question. In this section, the Maikop-type clays are overlain by coarse-gained sandstones and gravelstones, which grade upward into clayey sandstones and siltstones. Sediments in the middle part of the sequence contain diverse and abundant mollusks (Popov *et al.*, 1993b). The thickness of the Sakaraulian regional stage in the hypostratotype is about 230 m (Voronina *et al.*, 1991). The Sakaraulian sandstones are conformably overlain by sandstones of similar lithology, which yield the Kotsakhurian mollusks. Foraminifers have not been found in the stratotype area, but in the eastern part of the Kartli depression Sakaraulian sandstones are replaced by clays with sandstone interbeds, and foraminiferal assemblage from this area is composed of nonionids, *Uvigerinella californica, Bolivina* ex gr. *floridana*, and others (Archvadze, 1964).

Beyond the stratotype area, analogues of the Sakaraulian deposits are represented by the upper part of the Karadzhalga Formation and by the Ol'ginskaya Formation of the Ciscaucasia region. By lithology (clays), the upper part of the Karadzhalga Formation is similar to its lower part that is referred to the Caucasian regional stage, but it contains polyhaline foraminifers *Neobulimina* aff. *elongata, Caucasina* sp., and *Trochammina* aff. *florifera*, radiolarians, and pteropods. The Ol'ginskaya Formation is composed of carbonate-free clays with foraminifers *Neobulimina elongata, Bulimina tumidula, Bolivina floridana*, and others associated with mollusks (Volkova, 1962; Popov *et al.*, 1993b). The thickness of the formation ranges from 120 to 200 m.

Analogues of the Ol'ginskaya Formation, which yield foraminifers of the *Neobulimina elongata* assemblage, are defined in the northern Black Sea region, Crimea, and Kopetdag. Based on this assemblage, the following stratigraphic units are referred to the Sakaraulian regional stage: (1) Chernobaevka Formation of the northern Black Sea region, (2) Arabatskaya (formerly *Bathysiphon*) Formation of the Crimea, (3) Aradyk and Tsagan-Khak formations of the Volga–Don interfluve, (4) an uppermost part of the Kashkaraty Formation of Mangyshlak, (5) the middle part of the Aral Formation of the Aral region, (6) *Neobulimina elongata* Beds and Aktepinskaya Sands (partly) of the

Kopetdag (*Neogenovaya sistema...*, 1986; Popov *et al.*, 1993a; Goncharova and Popov, 1995; Nosovskii, 1993, 1998b).

Based on mollusc species in common, the Sakaraulian regional stage is correlated with the Eggenburgian and basal Ottnangian of the Western Paratethys and, via correlation with the latter, with the lower part of the Burdigalian Stage of the International stratigraphic scale (*Trudy 6-go Kongressa...*, 1976; *Neogenovaya sistema...*, 1986; Popov *et al.*, 1993b).

The Sakaraulian basin occupied, like the preceding Caucasian one, the eastern part of the Paratethys and communicated with the World Ocean via both the Western Paratethys in the west and the Indo-Pacific part of the Tethys in the southeast. As compared with the Caucasian sea, the Sakaraulian basin was smaller, because former sea areas in the north and east became desiccated. Sandy sediments of its coastal zone were inhabited by diverse shallow-water molluscan genera *Anadara, Glycymeris, Acanthocardia, Fragum, Arctica, Glossus*, and others. Deep zones of the basin covered by clayey mud hosted rare species of *Nucula, Nuculana, Palliolum*, and some other molluscan genera. Climate of the Sakaraulian time was very warm, as it is evident from clearly thermophilic character of marine molluscan species and terrestrial vegetation (Popov *et al.*, 1993a).

KOTSAKHURIAN REGIONAL STAGE

The Kotsakhurian regional stage (lower Miocene) was defined by Davitashvili (1933) who did not indicate however the geographic location of its stratotype. Judging from the first description, it is the section located northwest of the town of Kaspi in eastern Georgia (Kvaliashvili, 1962; *Stratotipy yarusov...*, 1975). In this section, the Kotsakhurian regional stage is represented by massive sandstones and siltstones with concretions. These rocks overlie the Sakaraulian strata and are overlain, with a sharp unconformity and erosional contact, by the Chokrakian conglomerates.

Because of the stratotype incompleteness and poor paleontological characterization, a more complete section of the Naderbazevi Ravine located north of the Metekhi railway station was selected for the stage hypostratotype (Popov and Voronina, 1983). In this section, the Kotsakhurian silty sandstones and clayey siltstones rest conformably upon the Sakaraulian strata (hypostratotype of the regional Sakaraulian stage) and are overlain with a significant hiatus by the Chokrakian layers. The impoverished Kotsakhurian assemblage of brackish-water mollusks consists of *Rzehakia dubiosa, Cerastoderma ivericum, C. lacustre, Eoprosodacna kartlica, Congeria subclaviformis*, and *Melanopsis impressa* (Popov, 1983), and concurrent foraminifers are represented by *Saccammina zuramakensis* and some other forms.

In other areas of the Ciscaucasia region, the Kotsakhurian regional stage includes the Ritsa and Zuramakent formations and the *Saccammina zuramakensis* Beds. Similar molluscan and foraminiferal assemblages are characteristic of the Mayachka and Korolevo formations of the northern Black Sea region and Crimea, and of the so-called *Oncophora* and *Saccammina zuramakensis* Beds of the Transcaspian region (*Neogenovaya sistema...*, 1986).

Based on the molluscan fauna, the Kotsakhurian regional stage is correlated with the upper part of the regional Ottnangian Stage of the Western Paratethys and, consequently, with a part of the Burdigalian Stage of the International stratigraphic scale (*Neogenovaya sistema...*, 1986).

In its dimensions and configuration, the Kotsakhurian basin was similar to the Sakaraulian one. Its salinity was lowered, and waters probably differed in composition from typical seawater to be suitable for existence of brackish-water and very rare euryhaline marine species. In the west, the Kotsakhurian basin was intermittently connected with the brackish-water Ottnangian basin that was favorable for faunal exchange between them (Popov and Voronina, 1983; Popov *et al.*, 1993).

THE LOWER–MIDDLE MIOCENE BOUNDARY

The lower–middle Miocene boundary is usually placed between the Langhian and Burdigalian stages at the level of 16.4 Ma (Berggren *et al.*, 1995). Some problems concerning the Burdigalian–Langhian boundary still wait their solution (Iaccarino, 2001). Although the Langhian stratotype is supplemented with its lower boundary stratotype (*Stratotypes...*, 1970), a lame selection of the stage stratotype proper (Cita and Premoli Silva, 1960) resulted in ambiguous interpretation of this stratigraphic interval and, correspondingly, of the lower–middle Miocene boundary (for discussion see Krasheninnikov *et al.*, 1999; Goncharova *et al.*, 2001). In the summarizing work by Berggren *et al.* (1995), the base of the Langhian Stage correlated with the base of the middle Miocene is marked by the first occurrence of *Praeorbulina glomerosa* and thus coincides with the base of the foraminiferal N8 Zone (Blow, 1959), as interpreted by Berggren *et al.* The N8 Zone by Blow is reduced in this summarizing work as its former lower part with *Globigerinoides bisphaericus* is referred to the N7 Zone. In opinion of Berggren *et al.* (1995), this modification leaves virtually unchanged the ranges of N7 and N8 zones by Blow. The last zone is defined by mentioned authors as the *Praeorbulina sicana–Orbulina suturalis* Interval Zone of (sub)tropical areas. Based on nannoplankton distribution, the same boundary is placed within the Martini's NN4 Zone (Berggren *et al.*, 1995) or, according to most recent data, between the NN4a and NN4b subzones (Iaccarino, 2001; and others). The Burdigalian–Langhian boundary is also marked by the appearance of sev-

eral characteristic pteropod genera, such as *Clio, Stylioola, Cuvierina*, and *Cavolinia* (Robba, 1971, 1972), and coincides with the boundary between the PN3 and PN4 zones of pectinid fauna (Demarcq, 1990, 1992; Ben Moussa and Demarcq, 1992). According to Berggren *et al.* (1995), the base of the Langhian Stage corresponds either to the Chron C5Cn2n or, what is more likely, to Chron C5Cn1n. In our opinion, the correspondence between the Burdigalian–Langhian and lower–middle Miocene boundaries is a most keen problem concerning the interval in question.

Controversial is also initial definition of the lower and middle Miocene in the Western Paratethys, i.e., the definition of boundary between the Karpatian and Badenian regional stages that is placed alternatively at first occurrence levels of either *Praeorbulina* (Cicha *et al.*, 1975a) or *Orbulina* (Cicha *et al.*, 1975b) forms. It should be noted, however, that European researchers decided ("by convention", Dercourt *et al.*, 1993, p. 226) to prefer the first appearance level of *Praeorbulina glomerosa*. Also ambiguous stratigraphic interpretation of Karpatian and Badenian nannofossil assemblages, and the age of the Karpatian Stage that is attributed to either the early Miocene (Rögl, 1996, 1999) or the early and middle Miocene (Hladilova *et al.*, 2000). *Globigerinoides bisphaericus* (zonal species of the Blow's N7 Zone) recently found by I. Cicha in the uppermost Karpatian beds (nannoplankton NN4b Zone) of continuous Moravian sections (information by A.S. Andreeva-Grigorovich) further complicates correlation between the Western Paratethys and Mediterranean region.

Published data on stratigraphy and correlation of Langhian, Karpatian, and Badenian sequences show a complete disagreement between researchers in interpretation of boundaries and zonal characteristics of these subdivisions. It is clear therefore that data obtained after the 6th Congress of the RCSMN (1975) demand revision of former concepts and, probably, reconsideration of relevant geological history of Mediterranean region and Paratethys.

TARKHANIAN REGIONAL STAGE

The Tarkhanian regional stage (uppermost lower–basal middle Miocene) was defined by Andrusov (1918). Its stratotype in the Cape Tarkhan of the Kerch Peninsula (the Sea of Azov coast) is now disturbed by landslides. A section of the Malyi Kamyshlak Ravine located 5.5 km east of the stratotype is selected for the hypostratotype (Nosovskii *et al.*, 1976). The Tarkhanian interval in this section corresponds to the clayey–marly, mainly carbonate sequence 110 m thick that rests conformably upon the upper Maikop clays and is overlain with a insignificant hiatus by the Chokrakian biohermal limestones and sandstones. The hypostratotype yields diverse micro- and macrofossil assemblages.

In most areas, the Tarkhanian regional stage is divided into three subunits: the lower Kuvinskii, middle Terek, and upper Argun beds. The last unit is frequently referred, partly (Zhizhchenko, 1940; Konenkova and Bogdanovich, 1994) or entirely (Zhizhchenko, 1959; Bagdasaryan, 1965, 1978), to the Chokrakian regional stage. In the stratigraphic scheme proposed in this work, the Argun Beds are included, in their entire range, into the Tarkhanian regional stage in line with views of Merklin (1950) and Nosovskii (Nosovskii *et al.* 1976, 1978; Nosovskii, 1998b), because the terminal Argun time marked, along with biotic changes, the facies and structural reorganization of the basin (Goncharova, 1989).

The Kuvinskii Beds defined in the central Ciscaucasia region (Merklin *et al.*, 1964) are represented by slightly carbonate clays (0.5 to 50 m) similar in lithology to underlying Kotsakhurian sediments, though differing from them in the occurrence of planktonic and benthic marine fauna with relic brackish-water Kotsakhurian forms (*Rzehakia dubiosa, Saccammina zuramakensis*).

The Terek Beds, which are defined in the eastern Ciscaucasia region (Zhizhchenko, 1937) and frequently termed as the Tarkhanian Marl or *Lentipecten corneus denudatus* Beds, are represented by marl (0.15 m) or calcareous clay (up to 25 m) yielding the abundant and diverse marine fauna. Abundant and widespread amid mollusks are polyhaline Mediterranean species of the *Lentipecten, Nucula, Neopycnodonte*, and *Aporrhais* genera. *Rzehakia* species are virtually missing and occur only in some areas of Georgia. Euryhaline benthic foraminifers coexist at this level with abundant polyhaline nodosariids and textulariids, and also with planktonic *Globigerina* (e.g., with *G. tarchanensis*), *Globorotalia*, and *Planorotalia* forms (Bogdanovich and Goncharova, 1976; *Neogenovaya sistema...*, 1986).

The Argun Beds first defined in the eastern Ciscaucasia Region (Zhizhchenko, 1937) are represented mostly by clays (up to 300–500 m) with abundant *Spiratella* ("*Spirialis* Clays") and scarce other fossils. They lack characteristic middle Tarkhanian mollusks, nodosariids and textulariids. Planktonic foraminifers are of low abundance as well. All these features point to a somewhat restricted water exchange of the basin with the open oceanic waters. Nevertheless, it was a sea basin, as it is evident from occurrence of planktonic foraminifers, echinoderms, and remains of deep-water luminous fishes (Goncharova, 1989; Goncharova *et al.*, 2001). In deep-water clayey facies bearing scarce fossils, the undivided Tarkhanian Stage is recognizable owing to occurrence of *Globigerina tarchanensis* and *Bolivina tarchanensis*. The total thickness of the Tarkhanian regional stage is up to 500 m.

It is quite difficult to correlate the Tarkhanian Stage with subdivisions of the Mediterranean scale and with regional stages of the Western Paratethys because of

ambiguously interpreted stage ranges in two last regions, where their stratotypes are incomplete (for discussion see Krasheninnikov *et al.*, 1999). The situation is aggravated by problems concerning the Tarkhanian regional stage itself (Gontsharova, 2001; Goncharova *et al.*, 2001). Its assemblage of planktonic foraminifers is lacking zonal species. Data on nannofossils from Tarkhanian sediments are controversial: based on their composition the stage in question is referred to the NN5 Zone either entirely (Andreeva-Grigorovich and Savytskaya, 2000) or partly so that the boundary between NN4 and NN5 zones appears to be within the basal upper Tarkhanian (Konenkova and Bogdanovich, 1994). We share the last viewpoint and correlate the Tarkhanian with the uppermost part of the NN4 Zone coupled with the basal interval of the NN5 Zone. In the proposed scale, the lower and upper parts of the Tarkhanian Stage are correlated with the uppermost Burdigalian and basal Langhian, respectively. The Tarkhanian also corresponds to the Karpatian and, probably, basal Badenian regional stages of the Western Paratethys.

The beginning of the Tarkhanian was marked by the onset of a prolonged faunal exchange between the Eastern and Western Paratethys, which evidently took place via the Dniester strait in the northwest and via the South Dobruja seaway in the south (Goncharova *et al.*, 2001). Simultaneously, the Eastern Paratethys was also connected with the East Mediterranean sea via the Middle Araks and Aleppo–Urfin straits, and with the Indo-Pacific realm of the Tethys through the Central Iranian basin (Goncharova and Shcherba, 1997; Goncharova *et al.*, 2001). The early Tarkhanian basin stretched from northeastern Bulgaria in the west to the Aral Sea and western Turkmenistan in the east. As compared with the Kotsakhurian sea, the basin expanded in the west and northwest. In addition, it became much deeper, comprising a spacious deep shelf (or lower subtidal zone) and pseudoabyss (150 to 300 m after Zhizhchenko, 1940).

Biota of the early Tarkhanian basin was diverse and included different groups of benthic and planktonic invertebrate organisms and fishes. Locally, some relicts of the brackish-water Kotsakhurian fauna were preserved, e.g., *Rzehakia dubiosa, Saccammina zuramakensis, Syngnathus altus* (Goncharova *et al.*, 2001).

In the middle and late Tarkhanian, deep areas of the basin enlarged, whereas connection with open oceanic basins became restricted that increased endemism of biota. The reduced water exchange was pulsating, and periods of H_2S contamination in bottom waters, when benthic biota became scarce or disappeared completely, alternated with periods of oxygenated conditions near the bottom. In the last case, deep bottom areas became populated again by benthic organisms. Among the latter, there were sometimes sea urchins, in addition to ophiurids, and deep-water fishes (luminous anchovies) appeared in the pelagic zone. By the end of the Tarkhanian, the basin shoaled. Despite all these changes however, the basin retained marine environments: its salinity was from 30 to 32‰ throughout the entire Tarkhanian and slightly lower in the middle and late Tarkhanian (Goncharova, 1989; Goncharova *et al.*, 2001).

CHOKRAKIAN REGIONAL STAGE

The Chokrakian regional stage (middle Miocene) was first defined in 1884 by Andrusov who established its stratotype along the eastern coast of the Chokrak Lake in the Kerch Peninsula, Ukraine, where only the lower part of the stage is exposed (8.8 m). The hypostratotype defined in the Malyi Kamyshlak Ravine is located immediately above the Tarkhanian hypostratotype. The Chokrakian regional stage of the hypostratotype is represented by a sandy–biohermal sequence (60 m thick) in the lower part and by clays with marl interbeds (30 m thick) higher in the section. These sediments rest unconformably on the upper Tarkhanian deposits and grade upward into the Karaganian strata. The boundary between the Chokrakian and Karaganian regional stages can be observed 2 km south of the hypostratotype, where it is marked by appearance of abundant *Spaniodontella gentilis*. The total thickness of the Chokrakian regional stage is up to 800 m. Accumulation settings of Chokrakian marine sediments are generally shallower, and their distribution area is larger as compared with these parameters of the Tarkhanian facies. The sediments reveal transgressive relationships with the older strata in marginal parts of the basin.

The Chokrakian regional stage is subdivided into the lower (Zyuk Beds) and upper (Bryk Beds) substages. The impoverished marine fauna of the lower Chokrakian Substage is more endemic in composition than the Tarkhanian one. Characteristic Chokrakian mollusks are *Aequipecten varnensis, Angulus fuchsi, Pitar laskarevi*, and *Cerithium cattleyae* (Goncharova, 1989). Concurrent foraminifers are represented only by benthic forms, predominantly by *Chokrakella* species and nonionids (*Florilus*). The nannofossil assemblage includes species characteristic of the NN5 Zone (Konenkova and Bogdanovich, 1994). The uppermost lower Chokrakian encloses the Belomechetskaya mammalian assemblage (central Ciscaucasia, Belomechetskaya Village) alternatively referred to the MN5 (Gabuliya and Bendukidze, 1984), MN6 (*Neogenovaya sistema...*, 1986), and basal MN5–uppermost MN6 (Lopatin, personal communication) zones.

The fossil assemblages of the upper Chokrakian include only endemic species. Abundance of bivalves sharply decreases at this level, and single gastropods are represented only by embryonic specimens. Polychaeta tubes of the *Ditrupa* genus occur locally in abundance (Goncharova, 1989). Benthic foraminifers represented by rare discorbids, elphidiids, and nonionids (peculiar *Florilus parvus* included) have dwarfish to aberrant appearance (*Neogenovaya sistema...*, 1986).

Some specific mollusks, such as *Donax tarchanensis*, *Ervilia praepodolica*, and *Barnea praeustjurtensis*, occur throughout the Chokrakian sequence.

Owing to their mollusks, characteristic foraminiferal species, and lithological properties (increased content of sandy material, occurrence of biohermal buildups), the Chokrakian sediments are reliably traceable throughout the Eastern Paratethys.

The Chokrakian can be correlated with the upper Langhian of the Mediterranean scale and with the upper lower Badenian (Moravian) of the Western Paratethys based on the following data: its range corresponds to the interval of the mammalian zones MN5–MN6; boundary between magnetostratigraphic chrons 15 and 16 is recorded within the uppermost Chokrakian (Muzylev and Pevzner, 1983); and the stage is between the Tarkhanian, the lower part of which corresponds to the Karpatian, and Karaganian that corresponds to the Wielichkian.

In the Chokrakian time, basin was shallow, with enlarged shoal zones. An island chain appeared in its axial part. The basin expanded northward and eastward (Goncharova *et al.*, 2002). It lost connections with the Western Paratethys (Goncharova, 1989; Goncharova and Il'ina, 1997, Goncharova and Shcherba, 1997) but communicated with the Central Iranian basin and Eastern Mediterranean in the southeast via the Middle Araks strait. The water exchange with Mediterranean and, probably, Mesopotamian basins took place via the Aleppo–Urfin strait. The progressive shoaling of the strait at the beginning of the middle Miocene (mid-Chokrakian) was favorable for migration of mammals and faunal exchange between Africa and Eurasia (Goncharova *et al.*, 2002).

Vast shoals that appeared in the early Chokrakian favored development of benthic organisms (mollusks, bryozoans, foraminifers, ostracodes) and algal–bryozoan bioherms. Planktonic biota was still dominated by pteropods (*Spiratella*), and nektonic organisms were represented by diverse fishes. Salinity in the Chokrakian basin was at least as high as 28‰ (Bagdasaryan, 1959, 1965; Goncharova, 1989), except for areas influenced by large rivers.

In the late Chokrakian time, the basin advanced further northward because of the enhanced river runoff and became isolated after closure of the Middle Araks strait. The transformation of hydrological regime into semimarine one made the water salinity close to that in the subsequent Karaganian basin (Bagdasaryan, 1959), and this event was responsible for a rapid biota impoverishment, extinction of some groups (*Spiratella*), and considerably reduced diversity of others (only Clupeidae survived amid fishes).

KARAGANIAN REGIONAL STAGE

The Karaganian regional stage (middle Miocene) was defined by Andrusov (1917a) who described its lectostratotype in the Uiratam Ravine of the Tyub-Karagan Peninsula, Mangyshlak region of Kazakhstan (*Stratotipy yarusov...*, 1975). In this section, the Karaganian sediments with *Spaniodontella gentilis*, *Mohrensternia barboti*, and other mollusks are separated by erosional boundary from the Paleogene clays. The contact with the overlying Konkian regional stage is not clear in the lectostratotype, because the *Pholads* (=Kartveli) Beds, also attributed to the Karaganian in our scale, are overlain by sandstones, which can be the early Sarmatian in age. In other section of the stratotype area in Mangyshlak, the *Pholads* Beds are conformably overlain by the Konkian strata with diverse marine fossils. In sections of deeper-water origin, the Karaganian sediments overly conformably the Chokrakian layers and are well distinguishable owing to occurrence of endemic molluscan genera *Spaniodontella* and *Mohrensternia* and of dwarfish foraminiferal species of *Discorbis, Cassidulina, Nonion*, and other genera.

Paleontological characteristics of Karaganian deposits are well known in northeastern Bulgaria, western Kazakhstan, northern Turkmenistan, and Georgia, where the stage is subdivided into three units: (1) the lower subdivision (Arkhasheni Beds after Zhgenti, 1981) bears abundant *Spaniodontella gentilis*; (2) the middle one (Varna Beds after Zhgenti, 1976, Melitopol Beds after Molyavko, 1950, and Turkmen Beds after Sudo, 1961) yields *Savanella andrussovi, Spaniodontella gentilis*, abundant *Ervilia pusilla*, several Mediterranean migrants (*Callista, Clausinella, Gafrarium, Alaba, Hadriania*, and others), *Neobulimina* and *Dendritina* foraminiferal genera, and scarce nannofossils; (3) the upper unit (Kartveli Beds, or *Pholads* Beds after Davitashvili, 1930) is usually marked by abundance of pholadids representing several *Barnea* species. Zhgenti (1976, 1991) proposed to consider the Kartveli Beds as an autonomous regional stage with the stratotype at the Khobi River near the Mukhuri Village (western Georgia). In our opinion, this idea based on the evolutionary succession of *Barnea* forms is sufficiently well grounded (Il'ina, 2000b). Nevertheless, we regard this unit in our scheme as beds (or substage) corresponding to the uppermost Karaganian, because it is recognizable in shallow-water facies only, being unrecognizable in many regions, where sections of deeper-water origin are lacking pholadids. In these sections, the upper Karaganian boundary is distinguishable based on the first appearance of polyhaline fossils characteristic of the overlying Konkian Stage. The maximum total thickness of the Karaganian sediments is 400 m.

The direct correlation of the Karaganian regional stage with Miocene stratigraphic units of the Western Paratethys and Mediterranean basin is difficult: its fauna is of endemic character, zonal species are lacking amid Mediterranean immigrants, and isotopic dates are unknown for the Karaganian sediments. Nevertheless, taking into consideration its position within the section and occurrence of evaporites, the Karaganian Stage is most likely correlative with the Wielichkian of the

Western Paratethys. In the Mediterranean scale, it presumably corresponds to the lower Serravalian. This is partly confirmed by data of Bogdanovich who established presence of index species of the nannoplankton NN5 Zone in the Karaganian sediments of the Kerch Peninsula and Dnepropetrovsk oblast of Ukraine (Barg, 1993).

The progressing isolation of the Eastern Paratethys that commenced in the late Chokrakian resulted in formation of the Karaganian spacious sea. This basin stretched from northeastern Bulgaria (Varna Bay) in the west almost to the Aral Sea in the east, forming here the Ustyurt gulf. In the north, the basin bays penetrated deep into land south of the latitude of 48°N, whereas its southern gulf occupied the modern Middle Araks depression and Nakhichevan trough and was populated by *Spaniodontella* and *Barnea* species.

Taking into consideration the low diversity and endemic composition of the Karaganian molluscan assemblage, it is possible to assume that this basin of the Eastern Paratethys was isolated from the World Ocean and had anomalous salinity. It was brackish-water in general, on the one hand, and could be locally hyperhaline, on the other, as it is evident from occurrence of evaporites (hypsum) of the Karaganian age. At the same time, evaporites could be deposited, particularly in the eastern and southeastern parts of the basin, under influence of climatic factor. Approximately at the mid-Karaganian (Varnean) time, the basin acquired a short-term and restricted communication with open seas that was favorable for immigration of some polyhaline taxa (*Callista, Clausinella, Gafrarium, Alaba*, some Muricidae, *Neobulimina elongata*, scarce nannoplankton).

Shallow areas of the basin accumulated sandy–calcareous sediments with frequent stromatolite interbeds. Karaganian sediments of a relatively deeper origin, such as clays with marl interlayers, are characteristic of the Kerch–Taman trough, eastern Ciscaucasia, and Trans-Caucasian region. Bottom waters in the deepest areas of these Karaganian basins were probably H_2S-contaminated, because relevant sediments are barren of benthic fossils (Zhizhchenko, 1940).

KONKIAN REGIONAL STAGE

The Konkian regional stage (middle Miocene) was first defined by Andrusov (1917a). He considered the *Venus konkensis* Beds, which are exposed along the Konka River near the Veselyanka Village, Zaporozh'e oblast of Ukraine, and have been originally described by Sokolov (1899), as the stage stratotype. The Konkian fine-grained sands of the stratotype rest unconformably on older Miocene coastal–terrestrial sediments, being overlain with a stratigraphic unconformity by lower Sarmatian coquina–sandy strata. The stratotype corresponds only to the upper part of the regional stage in question. Its beds yield not very diverse assemblages of mainly euryhaline marine mollusks (*Parvivenus konkensis, Acanthocardia andrussovi, Ervilia, Corbula, Sandbergeria*, and others) and foraminifers (small *Elphidium macellum, Ammonia* ex gr. *beccarii*, and others).

In a more complete sections of the stage (Transcaspian and Ciscaucasian regions), basal layers contain relatively diverse assemblages of polyhaline mollusks (*Glycymeris, Arca, Anadara, Chlamys, Europicardium, Parvicardium, Glans, Callista, Diloma, Alvania, Onoba, Spiratella*, and others), foraminifers (buliminids, peneroplids, miliolids, nonionids, elphidiids, globigerinids, and others), and ostracodes (*Cytheridea* and others), all characteristic of basins with normal salinity. This interval is known as the Sartagan Beds, whereas overlying sediments with prevalent euryhaline marine fauna and associated endemics are defined as the Veselyanka Beds of the Konkian regional stage (*Neogenovaya sistema...*, 1986). In our opinion, the term Sartagan is not valid, because basal Konkian layers are missing from the stratotype exposed in the eponymous ravine (Il'ina, 2000b). The total thickness of Konkian sediments does not exceed commonly 20 m, though locally it can be up to 50 m.

The Konkian Stage is well recognizable only in sections of shallow-water genesis, when its deposits rest on the Kartveli (*Pholads*) Beds of the Karaganian regional stage and are overlain by lower Sarmatian sediments. Deep-water Konkian deposits are similar in lithology to overlying Sarmatian strata and can be discriminated from the latter only based on finds of polyhaline microfauna, e.g., of *Spiratella* forms.

Konkian strata yield nannofossils enabling their correlation with the interval of NN6–NN7 zones (Andreeva-Grigorovich and Nosovskii, 1976; Minashvili, 1986; Muzylev and Golovina, 1987). Polyhaline genera *Discoaster* and *Rhabdosphaera* present among nannofossils point to the water exchange between the Konkian and open sea basins. Konkian sediments have not been dated by isotopic methods. Based on mollusks and microfossils, the Konkian regional stage is correlated with the upper part of the Badenian (Kosovian) of the Western Paratethys. Abundant *Globigerina bulloides* from relatively deep-water Konkian deposits of the Kerch Peninsula allow their correlation with the lower Kosovian of the Cis-Carpathian region (Barg, 1993). In the Mediterranean scale, the Konkian regional stage corresponds to the middle part of the Serravalian.

At the beginning of the Konkian time ("Sartagan" epoch), the Eastern Paratethys had relatively free connections with the World Ocean, and endemic pholadids of the Kartvelian time were replaced by diverse mollusks, nannoplankton, benthic and planktonic foraminifers. The water salinity increased to reach value close to the normal one (30‰ at least). The basin stretched from the southeastern Ustyurt in the east to southeastern areas of the Nikolaev oblast of Ukraine and even to the modern Dniester–Prut interfluve (Roshka *et al.*,

1968) and northeastern Bulgaria (Varna Bay) in the west.

The nearly normal hydrological regime of the early Konkian sea existed for a short time. Because of restricted connections with oceanic waters, the basin turned again into a semiclosed sea with semimarine hydrological environments (late Konkian time). Nevertheless, polyhaline Mediterranean elements occurring at different levels in the upper Konkian sequence indicate intermittent communication of the Konkian basin with open sea basins and immigration of marine biota. According to Il'ina (2000a, 2000b), at least two such episodes occurred in the late Konkian period: in the middle and at the end of this time span.

In the southeast of the Eastern Paratethys, water exchange between the Konkian and open sea basins probably occurred (Il'ina, 1995, 2000a; Goncharova and Shcherba, 1997) via straits, one of which existed in the Talysh zone and the other one connected the Middle Araks and Middle Kura depressions (Il'ina, 2000a). Connections with the Badenian basin of the Western Paratethys, if any, could be in the Dniester–Prut interfluve area only in the late Konkian time (Goncharova and Il'ina, 1997).

THE MIDDLE–UPPER MIOCENE BOUNDARY

This boundary is placed between the Serravalian and Tortonian stages of the International stratigraphic scale at the level of 11–11.2 Ma. It corresponds to the boundary between the Sarmatian s. str. (*Sarmartien*, 1974) and Pannonian (about 11.5 Ma) in the Western Paratethys and is distinguished within the uppermost middle Sarmatian in the Eastern Paratethys.

Based on nannofossils, the Serravalian–Tortonian boundary in the Mediterranean region is thought to be that separating NN8 and NN9 zones, or the other one distinguished in the upper part of the NN7 Zone (Berggren *et al.*, 1985). Similarly ambiguous is interpretation of the middle–upper Miocene boundary based on nannofossil finds in the western part of the Eastern Paratethys. According to these finds, the boundary in question is assumed to be either between NN8 and NN9 (Mărunteanu *et al.*, 1998) or between NN7 and NN8 zones (Olszewska, 1999; Garecka and Jugowiec, 1999).

SARMATIAN REGIONAL STAGE

The Sarmatian regional stage (uppermost middle–basal upper Miocene) was defined by Barbot de Marny (1866). The lectostratotype of the stage (Paramonova and Belokrys, 1972) is located in the vicinity of the Shirokoe Village at the left bank of the Ingulets River (Dnepropetrovsk oblast, Ukraine). In this section, the Sarmatian sequence, relatively complete though with minor hiatuses, rests on the erosion surface of Paleogene strata and is overlain, also with stratigraphic unconformity, by Maeotian sediments. In a more complete section of the Skotovataya Ravine near the Veselyanka Village (Zaporozh'e oblast, Ukraine), Sarmatian sediments conformably overlie the Konkian regional stage and are overlain by the Maeotian strata; this section is described as a hypostratotype of the stage (Kulichenko *et al.*, 1979).

The Sarmatian is divided into three substages: lower (Volhynian), middle (Bessarabian), and upper (Khersonian), which can be subdivided, in turn, into beds in the case of shallow-water facies.

The lowermost Kuzhora Beds of the Sarmatian (Kolesnikov, 1935), lectostratotype of which is established at the Konka River in southern Ukraine (Belokrys, 1963, 1976), bear *Plicatiformes praeplicatus* and *Obsoletiformes lithopodolicus ruthenicus* whereas the overlying Zbruch Beds (Didkovskii, 1964) with lectostratotype in the Bogdanovskii quarry of southern Ukraine (Belokrys, 1963, 1976) contain *Plicatiformes plicatus plicatus* and *Obsoletiformes obsoletus. Ervilia dissita, Mactra eichwaldi*, and other molluscan species are typical of lower Sarmatian shallow-water facies in contrast to *Abra reflexa* characteristic of deeper-water facies. The Zbruch Beds yield in addition *Mactra andrussovi* and *Inaequicostates* species. The middle Sarmatian with more diverse bivalves having larger shells can also be subdivided into the lower Novomoskovsk and upper Dnepropetrovsk–Vasil'evka Beds; lectostratotype of the former is defined in the type area of the Zbruch Beds (Didkovskii, 1964), and that of the latter is established at the Ingulets River in southern Ukraine (Paramonova and Belokrys, 1972). The shallow-water facies of the Novomoskovsk Beds contain *Plicatiformes plicatus plicatofittoni, Mactra vitaliana*, and *Venerupis ponderosus*, whereas coeval strata of deep-water origin yield *Cryptomactra pesanseris* and other molluscan species. The shallow-water facies of the Dnepropetrovsk–Vasil'evka Beds enclose *Plicatiformes fittoni, Mactra fabreana*, and several *Obsoletiformes* species, while their deep-water facies bear the molluscan assemblage similar to that of the Novomoskovsk Beds (Il'ina *et al.*, 1976; Nevesskaya *et al.*, 1986; Paramonova, 1994). The lower and middle substages contain also diverse assemblages of other invertebrates, e.g., of gastropods, foraminifers, and ostracodes, which are largely represented, like bivalve mollusks, by endemic species of euryhaline marine genera.

The upper substage of the Sarmatian regional stage includes the lower Katerlez Beds (Kolesnikov, 1935), the molluscan assemblage of which consists of *Mactra* (*Chersonimactra*) forms, and the upper Mitridat Beds (Kolesnikov, 1935) enclosing bryozoan–algal bioherms. Sections at the Ingulets River (Paramonova and Belokrys, 1972) and in the Kerch Peninsula (Paramonova, 1994) are selected respectively for lectostratotypes of these units.

The total thickness of the Sarmatian sediments in depressions is estimated to be 700–750 m.

The substages mentioned above are easily recognizable and correlative throughout the vast territory from the eastern Serbia and northeastern Romania in the west to western Kazakhstan and western Turkmenistan in the east. In the Western Paratethys, there are distinguishable the lower Sarmatian (Volhynian Substage), the lower half of the middle Sarmatian (so-called Sarmatian s. str.), and the regional Pannonian Stage above them.

Based on distribution of nannofossils, the lower Sarmatian deposits of Romania are correlated with the NN7 Zone and lower part of the NN8 Zone; the middle Sarmatian corresponds here to the upper part of the NN8 Zone and NN9 Zone, and the upper Sarmatian probably spans the upper part of the NN9 Zone and basal part of the NN10 Zone (Papaianopol and Mărunteanu, 1993; Mărunteanu *et al.*, 2000). In the Carpathian foredeep, the Sarmatian s. str. was correlated with the upper part of the NN6 Zone and NN7 Zone (Olszewska, 1990; Garecka and Jugowiec, 1999).

According to fission-track dating, the lower boundary of the Sarmatian regional stage is estimated to be at the level of 13.6 to 13.7 Ma (Chumakov *et al.*, 1984; Chumakov, 1993). In the Western Paratethys, it is regarded as either 13.0 (Rögl, 1998) or 13.6 Ma old (Vass, 1999). In opinion of Chumakov, the lower–middle, middle–upper and upper Sarmatian boundaries are 12.2, 11.2, and 9.3 Ma old, respectively.

Based on these age determination and some nannoplankton taxa, the Sarmatian regional stage of the Eastern Paratethys is correlated with the Sarmatian s. str. (*Sarmatien*, 1974) and lower Pannonian of the Western Paratethys, on the one hand, and with the upper Serravalian–lower Tortonian interval of the Mediterranean stratigraphic scale, on the other.

By the beginning of the Sarmatian, the Paratethys lost connections with open seas, and instead the late Konkian and late Badenian basins there was formed a vast semimarine basin that intermittently communicated with the Mediterranean Sea. The early Sarmatian basin stretched from the Alps in the west to the Aral Sea in the east and consisted of several autonomous basins (Pannonian, Dacian, Euxinian, and Caspian) interconnected via straits. In the north, the basin waters entered deep into paleoriver valleys.

Salinity in the early Sarmatian Paratethys lacking true polyhaline invertebrates, except for rare planktonic foraminifers, was low, about 14–15‰, and diversity of molluscan and foraminiferal assemblages was low as well. In the western part of the basin, salinity was slightly higher, probably approximating 16–18‰ (Kojumdgieva, 1969; Paramonova, 1994). This assumption is consistent with available isotopic data (Kiyashko, 1984; Kiyashko and Paramonova, 1987).

In the middle Sarmatian, particularly in its second half, the basin area decreased. Salinity lowered probably to values below 15‰, but intermittent restricted connections with the Mediterranean Sea via the Western Paratethys still existed (Belokrys, 1976; Venglinskii, 1975; Roshka, 1987; Paramonova, 1994; Il'ina, 1998), though they were imperceptible in the eastern part of the basin. The water exchange between Pannonian and Dacian basins ceased in the mid-Sarmatian as a result of the commenced closure of the Trans-Carpathian seaway, and the former turned into the brackish-water lake with the specific endemic (Pannonian) fauna.

In the late Sarmatian time, the basin further decreased in size, and its salinity lowered to 4–9‰ (Paramonova, 1994). The Eastern Paratethys turned into a completely closed basin. A brief ingression of the late Sarmatian sea into the eastern part of the Pannonian region is evidenced by *Chersonimactra* species found in Transylvania (Iliescu, 1971; Lubenescu, 1971; Gräf *et al.*, 1973).

MAEOTIAN REGIONAL STAGE

The Maeotian regional stage (upper Miocene) was distinguished by Andrusov (1890) in the stratotype at the western coast of the Kerch Strait near the town of Arshintsevo south of Kerch (Ukraine). In this section, the stage is composed of alternating detrital limestones, coquinas, and clays resting upon upper Sarmatian bryozoan limestones (the contact is observable in the neighboring Yanysh-Takyl section). The stage sediments are overlain by lower Pontian silty clays.

The Maeotian regional stage is subdivided into the lower (Bagerovian) and upper (Akmanaian) substages defined by Karlov (1937) in the Crimea. The lower substage yields mainly endemic species of Mediterranean taxa: *Dosinia, Mytilaster, Venerupis, Arba*, and *Ervilia* genera of bivalves and *Rissoa, Mohrensternia, Cerithium, Potamides*, and *Bittium* genera of gastropods. Foraminifers are represented mainly by euryhaline genera *Quinqueloculina, Elphidium, Articulina, Discorbis*, and others. Prevalent amid ostracodes are representatives of *Leptocythere, Xestoleberis*, and *Loxoconcha* genera. All these faunal groups point to abnormal marine environments in the early Maeotian basin, although rare polyhaline species occurring at some levels among benthic and planktonic foraminifers, nannoplankton (Semenenko and Lyul'eva, 1978; Bogdanovich and Ivanova, 1997), gastropods (Il'ina, 1972, 1980, 2000a), bivalves (Nevesskaya *et al.*, 1993), and ostracodes (Arevadze, 1987) suggest episodes of brief communication with open sea basins.

The upper Maeotian Substage yields brackish-water mollusks associated with scarce marine taxa. Among ostracodes, there are many freshwater species, and foraminiferal assemblage is of a low diversity. In some areas (western Georgia, Kerch Peninsula), brackish-water species occur in association with rare polyhaline molluscs, nannofossils, and diatoms. Assemblages of this kind suggest that the late Maeotian basin was episodically connected with oceanic basins. The total

thickness of the regional stage under consideration is 500–700 m.

The lower boundary of the stage is usually conformable, though changeable in terms of lithology. It is recognizable at the first occurrence level of marine fauna. The upper boundary is placed at the appearance level of Pontian brackish-water cardiids.

It should be also noted that the Dacian part of the Ponto-Caspian region (Romania, Bulgaria, Moldova) represented at the incipient Maeotian time a brackish-water or even freshwater basin (or basins) influenced intermittently by seawater ingressions, as it is established here in the lower part of the Bagerovian Substage composed of alternating fresh- to brackish-water and marine sediments. In our opinion, such facies relationships imply that idea of Andreescu (1973) to consider the lower Bagerovian interval as an autonomous Zhitian Substage is unacceptable.

Some Maeotian sections, including those located beyond southern Russia, contain nannofossils whose stratigraphic ranges are ambiguously interpreted: the lower Maeotian is thought to be corresponding to the NN9 (Bogdanovich and Ivanova, 1997) or NN10–basal NN11 zones (Mărunteanu and Papaianopol, 1998; Mărunteanu *et al.*, 2000), and the upper substage was correlated with the NN10 (Semenenko and Lyul'eva, 1978) and NN11 zones (Mărunteanu and Papaianopol, 1998; Mărunteanu *et al.*, 2000). Most likely, the lower and upper substages correspond to the greater part of the NN10 Zone and to the lower half of the NN11 Zone, respectively.

The following age values have been obtained by the fission-track method (Chumakov *et al.*, 1988a, 1988b, 1996; Chumakov, 1993): 9.26–9.36 Ma for the lower boundary of the Maeotian regional stage, 8.0–8.4 Ma for the lower–middle Maeotian boundary, and 7.0 Ma for the upper boundary of the stage.

Based on these data, the Maeotian regional stage can be correlated with the upper part of the Tortonian Stage of the Mediterranean scale and with the upper half of the regional Pannonian Stage of the Western Paratethys.

Like in the preceding period, the late Maeotian–late Pannonian Paratethys was separated into the western (Pannonian) and eastern (Dacian–Euxinian–Caspian) basins completely isolated from each other. The Pannonian basin with the Caspian-type salinity ranging from 8 to 15‰ (*Pannonien*, 1985; Kázmér, 1990), was still populated by brackish-water fauna and flora representing the endemic molluscan, ostracode, dinoflagellate, and nannoplankton taxa.

The Eastern Paratethys corresponded to an abnormal marine basin originated in response to sea-level rise in the middle Tortonian time (Rögl and Steininger, 1983). The water exchange between the early Maeotian sea and open ocean was likely realizable via some intermediate basin in the southeast (Il'ina *et al.*, 1976; Il'ina, 1980, 2000a; Nevesskaya *et al.*, 1984, 1986) and via the Aegean–Thracian semimarine basin in the southwest, where the latter might have a restricted connection with the Mediterranean Sea of the middle Tortonian– early Messinian time (Il'ina, *et al.*, 1976; Stevanovich and Il'ina, 1982; Shcherba *et al.*, 2000).

PONTIAN REGIONAL STAGE

The Pontian regional stage (uppermost upper Miocene) was defined by Barbot de Marny (1869). Its lectostratotype is located in the vicinity of Odessa (Ukraine), where Pontian sediments rest conformably, as is assumed, upon Maeotian clays and are overlain with a hiatus by the Quaternary loess sequence.

Inasmuch as only the lower Pontian interval is exposed in the stratotype, a section at the western shore of the Kerch Strait near the town of Arshintsevo (south of Kerch, Ukraine), where it is composed of clays (basal part) and loose coquinas and has been repeatedly described (Andrusov, 1917b; 1923; Eberzin, 1947, 1967; Nevesskaya and Stevanovich, 1985), is proposed to be a neostratotype (*Stratotipy yarusov...*, 1975). The Pontian regional stage is represented almost completely in this section, although its uppermost layers seem to be missing here, and the upper boundary with the Kimmerian regional stage is not observable. The thickness of the stage under consideration is at maximum 35 m.

The Pontian regional stage is subdivided into two substages: the lower Novorossian (Andrusov, 1923; southern Ukraine) consisting of the Evpatoriya and Odessa beds, and the upper one represented by the Portafer and Bosporus beds.

The Evpatoriya Beds defined by Davitashvili (1937) in the Crimea are known only in two localities, where they contain an extremely impoverished assemblage of brackish-water molluscan genera *Eupatorina, Dreissena, Congeria*, and *Theodoxus*. The overlying Odessa Beds first described by Mikhailovskii (1909b) in southern Ukraine yield brackish-water genera *Pseudocatillus, Euxinicardium*, and *Paradacna* in association with marine species *Parvivenus widhalmi*. The inherited Maeotian mollusks are represented by *Congeria* forms and rare *Abra tellinoides*.

The Portafer (Stevanovich, 1951) and overlying Bosporus Beds (Andrusov, 1923) enclose a more diverse fauna of brackish-water mollusks. Species *Congeria subrhomboidea* occurring in the former is missing from the latter.

The diverse molluscan assemblages occur only in shallow-water Pontian sediments, whereas deeper-water clayey facies of the stage yield only rare species of *Paradacna, Valenciennius*, and some other genera. None of marine species was found in the upper Pontian. The stage is up to 450 m thick in depressions. In addition to mollusks, Pontian sediments contain euryhaline marine (*Leptocythere, Loxoconcha*, and others) and brackish-water (*Caspiocypris, Pontoniella, Caspiolla, Bakunella*) ostracodes. The foraminiferal assemblage is extremely impoverished and consists mostly of euryha-

line species of genera *Quinqueloculina, Elphidium*, and *Ammonia.*

The lower boundary of the Pontian regional stage is either conformable in depressions or distinctly transgressive in marginal parts of the basin, where sediments of the Novorossian Substage overly the Neogene continental formations or Sarmatian and Karaganian marine facies. The Novorossian sediments are widespread from eastern Serbia, Romania, and Bulgaria in the west to Mangyshlak, Ustyurt, and West Turkmenistan lowland in the east, being easily correlative owing to their specific molluscan and ostracode assemblages. The upper Pontian is represented by distinctly regressive facies, and this interval in most areas corresponds to either hiatus or accumulation period of continental sediments.

Rare nannofossils from Pontian sediments are represented only by species of wide stratigraphic ranges. Their relatively diverse assemblage is known only in Romania, where the lower Pontian is correlated with the NN11 Zone, and the upper substage is arbitrarily attributed to the NN12 Zone (Mărunteanu and Papaianopol, 1998). The Pontian regional stage spans most likely the upper half of the NN11 Zone and a part of the NN12 Zone.

According to radiometric dates (Chumakov *et al.*, 1988a, 1988b, 1996; Chumakov, 1993, 2000), the Pontian Stage base is dated back to 7.1 Ma. The same date is accepted in recent Neogene scales of the Mediterranean region and Paratethys (Rögl, 1998; Steininger and Wessely, 2000). The upper stage boundary in these scales is at the level of 5.2 to 5.3 Ma.

The estimated time span is at variance with paleomagnetic data implying the reversed polarity of rocks in the Pontian interval (Pevzner in Semenenko, 1987; Trubikhin in *Pontien*, 1989; Molostovskii and Khramov, 1997) According to Trubikhin, the Pontian corresponds to the upper Messinian and Chron C3r, i.e., to the interval from 5.9 to 5.4–5.2 Ma. Pevzner (personal communication) regards the Pontian as corresponding to the interval of 7.5 to 6.74 Ma (dates are corrected using the new scale).

Taking into consideration some indirect data (paleogeographic and others), and compositions of brackish-water mollusks and dinocysts from the lower Pontian and upper Messinian, the Pontian regional stage should be correlated most likely with the upper part of the Messinian Stage accepted in the Mediterranean scale (Popov and Nevesskaya, 2000). In the western Paratethys, sediments equivalent to the lower Pontian are those with the molluscan assemblage that differs from that of the Novorossian Substage and is composed of descendants of the Pannonian taxa. Judging from their position below the upper Pontian Portafer Beds, these sediments can be referred to the lower Pontian, although their base is undeterminable. As for the upper Pontian Bosporus Beds, they correspond to basal *Paludina* Beds of the Western Paratethys.

During the Pontian period, water exchange between the Western and Eastern Paratethys was restricted first and rather intense later on. In the initial Pontian time, the Pannonian basin was similar in configuration and dimensions to the previous one. Having no or restricted communication with the Eastern Paratethys at the very beginning of the Pontian, it communicated with the latter in the mid-Pontian (Portaferian) time through the narrow Portafer (Trans-Carpathian) strait (*Pontien*, 1989, Fig. 5), though fauna, especially mollusks, predominantly migrated from the Western to Eastern Paratethys. The water salinity remained unchanged. During the late Pontian (Bosporus time), the indivisible Western Paratethys disappeared and was replaced by several isolated lakes.

The Eastern Paratethys of the early Pontian time consisted of the Dacian (in fact, a large western gulf of the Euxinian basin), Euxinian, and Caspian basin. The last one communicated with the Euxinian sea via the wide Stavropol seaway, and the Thracian strait connected the Euxinian sea with the Thracian–Aegean gulf of the Messinian sea (Kolesnikov, 1940; Gillet, 1961; Il'ina *et al.*, 1976; Nevesskaya *et al.*, 1986; *Pontien*, 1989; Popov and Nevesskaya, 2000).

It is difficult to estimate salinity values in the early Pontian basin, but its water has probably similar composition to that in the modern Caspian Sea, i.e., differed from normal seawater (Nevesskaya *et al.*, 1986). Being of brackish-water type, the early Pontian basin communicated however with other basins, as it is evident from abundant remains of euryhaline marine species *Parvivenus widhalmi*, which were also widespread in the Thracian–Aegean gulf of the Messinian sea.

At the beginning of the late Pontian (Portaferian time), the Eastern Paratethys became significantly reduced in area. The Caspian basin was separated from the Euxinian one, and seawaters retreated into region of the modern central to southern Caspian Sea. The southwestern part of the Caspian basin situated in Transcaucasia somehow communicated with the Euxinian basin throughout the Pontian Age, because the upper Pontian deposits of Azerbaijan yield molluscan species, which also occur in the upper Pontian of the Euxinian and Dacian basins (Nevesskaya *et al.*, 1986). The Pontian basin communicated with the Mediterranean Sea via the Thracian–Aegean gulf probably until the Portaferian time (Rögl *et al.*, 1991), i.e., till the desiccation of the latter. Salinity was like that of the early Pontian. The maximum depth of the late Pontian basin is unknown because deepwater facies of that time are not recorded.

During the second half of the late Pontian (Bosporian time), the Paratethys decreased further in size. The Dacian and Euxinian basins were still communicating with each other, although connections were more restricted than those of the Portaferian time, as it can be inferred from the high endemism of molluscan faunas from both basins. The Caspian and Euxinian basins of

the same time remained isolated from each other, being somehow interconnected in the southwest.

As a result of the terminal late Pontian regression, the entire region of northern Black Sea, modern Sea of Azov–Black Sea shelves included, emerged above the sea level (Semenenko, 1993). Nevertheless, areas located southward (central Black Sea) should be under water, otherwise the brackish-water fauna whose descendants became widespread during the subsequent Kimmerian Age would become extinct.

Factors responsible for the early Pontian transgression and subsequent late Pontian regression are not clear. In any case, a discharge of the late Pontian basin into the Messinian sea suggested as explanation for the regression (Semenenko and Teslenko, 1994) seems doubtful, because the Bosporian molluscan fauna would migrate in this case into the latter that did not happen, since the so-called Pontian or Lago-Mare fauna lacks any typical Bosporian species.

THE MIOCENE–PLIOCENE BOUNDARY

This boundary is placed between the Messinian and Zanclean stages at the level of 5.3 Ma (*GSSP*, 2000). In the Eastern Paratethys, it corresponds to the Pontian–Kimmerian boundary (Chumakov, 2000). There are also different standpoints, according to which the Miocene–Pliocene boundary should be drawn within the Kimmerian (Semenenko and Pevzner, 1979; Semenenko, 1987).

KIMMERIAN REGIONAL STAGE

The Kimmerian regional stage (lower Pliocene) was established by Andrusov (1907–1908). Its lectostratotype corresponds to section exposed along the western coast of the Kerch Peninsula near the town of Arshintsevo, south of Kerch, Ukraine (*Stratotipy...*, 1975), and has been thoroughly described by Eberzin (1947, 1967). The stage is incomplete in the stratotype, as its lower Azov Beds are missing. The basal Kimmerian rusty–brown oolitic and molluscan shelly beds locally cemented by sandy–clayey material rest upon upper Pontian coquinas (Bosporus Beds). They grade upward into a sequence of ferruginate sandy clay with ferruginous molluscan casts, pure to sandy clay, and sands with scattered shells. These Kimmerian sediments are conformably overlain by fossil-free sandy clays (Kuyal'nik) of the Akchagylian regional stage.

The Kimmerian is divided in two, the lower (Azov Beds) and upper substages, the latter spanning interval of the Kamyshburun and Pantikapei beds. The Azov Beds (Vassoevich and Eberzin, 1930; Kerch Peninsula) widespread along the Sea of Azov coast of the Kerch Peninsula are composed of coquinas, sands, and, less commonly, of clays. Their molluscan species belong to genera *Macradacna, Panticapaea, Stenodacna*, and *Pachydacna* s. str., which are unknown from the underlying upper Pontian sediments, though the other group consists of specific representatives of genera occurring in the latter (*Paradacna deformis, Oraphocardium alatoplanum, Pseudocatillus azovicus, Stenodacna praeangusticostata*, and others). The overlying Kamyshburun Beds (Andrussow, 1886; Kerch Peninsula) corresponding to the "ore horizon" and contain abundant and diverse species of genera characteristic of the Azov Beds. Many of them are large-size endemics (*Arcicardium acardo, Pontalmyra gourieffi, P. crassatellata, Prosodacna macrodon*, and others). The Pantikapei Beds (Davitashvili, 1933; Taman Peninsula) with the same generic composition of malacofauna recorded extinction of several species, being simultaneously marked by appearance of some new forms (*Macradacna meridionalis, M. maxima*, and others less abundant species). *Macradacna meridionalis. M. maxima*, and associated rare *Prionopleura colchica, P. krestovnikovi, Pachydacna anapensis*, and *Pontalmyra voskoboinikovi* represent most specific fossils of the beds. In addition to bivalve mollusks, the Kimmerian deposits yield gastropods and abundant ostracodes of the *Caspiolla, Bakunella, Caspiocypris*, and other genera.

The Kimmerian deposits are up to 550 m thick (in the Taman and West Cuban' troughs).

The lower boundary of the Kimmerian regional stage is usually unconformable, as the lower Azov Beds (and, probably, uppermost Bosporus Beds of the upper Pontian) are frequently missing. The conformable contact between the Azov and underlying Bosporus Beds is observable in some sections only. The upper boundary of the Kimmerian (below Kuyal'nik Beds) is conformable.

The lower boundary of the regional stage in question is variably dated back to 5.3–5.2 Ma (Chumakov, 1993, 2000), 5.4–5.2 Ma (Trubikhin in Chumakov *et al.*, 1996), 6.2–6.1 Ma (Pevzner in Semenenko, 1987), or 6.7 Ma (Pevzner, personal communication; the data recalculated based on the new scale). The upper boundary is unambiguously placed at the level of 3.5–3.4 Ma. Accordingly, the Kimmerian is correlative mainly with the Zanclean of the Mediterranean scale. This is also supported by Kimmerian nannofossils characteristic of NN11–NN13 zones (Semenenko and Lyul'eva, 1978; Semenenko, 1987). The Kimmerian most likely spans the upper part of the NN12 Zone and NN13 Zone, though the upper Kimmerian layers can be younger in accord with data on *Ceratolithus acutus* found in the Azov Beds (Lyul'eva, 1989). The Kimmerian regional stage corresponds to the middle part of the *Paludina* Beds in the Western Paratethys and to the Dacian regional stage in western areas of the eastern Paratethys (eastern Romania).

In the Kimmerian–Dacian time, the Paratethys consisted of the Dacian and Euxinian basins. It is not inconceivable that the Caspian basin also existed at the beginning of the Kimmerian time. All these basins remained brackish-water, and their benthic communi-

ties consisted of mollusks and ostracodes inherited from the Pontian basin.

Nevertheless, despite the fauna succession, the terminal Pontian orogenic phase and regression triggered erosion and formation of unconformity, because the uppermost Pontian and lower Kimmerian sediments are absent in many areas of the Euxinian region (Andrusov, 1929; Eberzin, 1967, 1968; Semenenko, 1987, 1993). Also remarkable were the Kimmerian events of local rising and subsidence, e.g., in the Kerch–Taman area, where development of mud volcanism took place in some depressions.

The Euxinian basin communicated in the west with the smaller Dacian basin via the narrow Rhain strait. The Euxinian basin largely occupied areas of the modern Black Sea and Sea of Azov, forming the Azov gulf in the north and the Rioni gulf in the east. In the southeast, the basin probably retained a restricted connection with the Babadzhan basin that appeared in the late Pontian and turned into the late Kimmerian, completely isolated Balakhan basin that occupied the modern South Caspian basin and subsided areas of Azerbaijan and western Turkmenistan.

Salinity in the Kimmerian basin was probably lower than that in the Pontian one, because the freshwater fauna (unionids, viviparids, and others) became more widespread. Waters in the basin were enriched in Fe-compounds responsible for local (Kerch and Taman peninsulas) deposition of iron ores. The beds of ferriferous–siliceous sediments accumulated when chemogenic sedimentation prevailed over the terrigenous one. As is assumed, Fe-rich sediments were deposited under conditions of warm climate and high influx of Fe-oxides partly transformed during diagenesis into leptochlorite (Semenenko, 1975b, 1987). The subtropical climate of that time is inferable for the northern Black Sea region from development of red laterite weathering crust in adjacent land areas (Muratov, 1964). The high water temperature and, probably, the elevated content of Fe-compounds in water were likely favorable for the dimension growth of molluscan shells, particularly in the late Kimmerian.

The Dacian basin of the Kimmerian (=Dacian) time was shallow and less saline than the Euxinian basin. In the terminal Kimmerian, it turned into a freshwater lake.

AKCHAGYLIAN REGIONAL STAGE

Andrusov (1896) was first to recognize the Akchagylian regional stage (middle–upper Pliocene). The stage lectostratotype is located near the Ushak Well in the Krasnovodskii Peninsula, Turkmenistan (*Stratotipy yarusov...*, 1975) and has been described in several publications (Dvali *et al.*, 1932; Ali-Zade, 1961; Chel'tsov, 1965; Danukalova, 1996). The basal Akchagylian layers are not observable in this section, but in the neighboring section between Kaskarbulak and Syul'men, they rest transgressively upon the red-colored Pliocene sediments (Andrusov, 1896). In the lectostratotype, the Akchagylian regional stage is separated from overlying Apsheronian sediments by the erosion surface (Ali-Zade, 1961), although in neighboring areas the boundary between these stages is conformable (Trubikhin, 1977).

The Akchagylian interval of the lectostratotype is composed of alternating silt, clay, sand, sandstone, marl, oolitic limestone, coquina, and conglomerate layers. The lower layers enclose bivalves of the *Aktschagylia, Avimactra,* and *Cerastoderma* genera and gastropod genera *Potamides* and *"Clessiniola"*. In the middle part, these taxa coexist with bivalves *Andrussella, Miricardium, Andrussovicardium,* and *Avicardium.* Among these molluscan genera, only *Cerastoderma* and *Aktschagylia* occur buried in the upper Akchagylian strata in association with brackish-water *Dreissena* and *Theodoxus.*

The thickness of the Akchagylian sediments in some areas is as high as 600–750 m.

There is no uniform view on subdivision of the Akchagylian into substages or beds. Stratigraphic units with paleontological characteristics outlined by Kolesnikov (1936, 1940) and termed by Paramonova (1994) as the Ushak, Umchal, and Suprimchek beds can be defined only in central and southern areas (Turkmenistan, Azerbaijan, eastern Georgia, Dagestan, middle part of the North Caspian depression). In the vast northern region (Volga and Kama river basins, Cis-Urals), and in western areas flooded during the Akchagylian sea transgression (Sea of Azov localities, Manych, Cis-Caucasus, Taman and Kerch peninsulas), they are virtually not recognizable, because their marine molluscan fauna is extremely impoverished.

In opinion of other researchers (Ali-Zade, 1961, 1967, 1969; Yurevich, 1966; Yatchenko, 1967; Trubikhin, 1977; Gurarii and Trubikhin, 1980; Nevesskaya and Trubikhin, 1984; Danukalova, 1996), the Akchagylian should be subdivided based on transgressive–regressive cycles, which do not coincide with the stages in development of the molluscan fauna. As a result, local stratigraphic schemes are currently in use for different distribution areas of the Akchagylian sediments. In areas, where the succession of molluscan fauna is easily traceable, the lower or Ushak Beds (Kolesnikov, 1936, 1940; Paramonova, 1994) bear an assemblage of several molluscan genera, such as *Cerastoderma, Aktschagylia, "Clessiniola,"* and some others. The middle or Umchal Beds contain a more diverse assemblage, which includes, in addition to mentioned forms, abundant species of endemic molluscan genera *Andrussovicardium, Miricardium, Acobaecardium, Avicardium, Raricardium,* and *Andrussella.* The upper or Suprimchek Beds yield only *Cerastoderma, Aktschagylia,* and brackish-water *Dreissena* species.

The Akchagylian sediments also yield foraminifers (*Bolivina, Cassidulina,* and others) and abundant ostra-

codes of diverse euryhaline genera *Leptocythere, Loxoconcha, Denticulocythere, Candona*, and brackish-water *Cypria, Prolimnocythere, Cytherissa*, and others characteristic of desalinated sedimentation settings.

The Kuyal'nik Beds or Formation (Sintsov, 1875; Mikhailovskii, 1909a) composed of shallow-water sands, sandstones, and clays with marl interbeds represent a stratigraphic analogue of the Akchagylian sediments in the Euxinian basin. They enclose rare bivalves of the *Lymnocardium, Pseudocatillus, Prosodacna*, and *Dreissena* genera. In some areas of the Azov–Black Sea region, the Kuyal'nik sediments host interbeds with the true Akchagylian mollusks. The latter were found in the basal Kuyal'nik Beds in the northern coast of the Sea of Azov (Semenenko, 1966). In the Taman and Kerch peninsulas, where sediments above the beds with *Dreissena theodori* and *Pachydacna kujalnicensis* bear the Akchagylian fauna, they were defined as the Taman Beds (Eberzin, 1931).

Inasmuch as the Akchagylian fauna occurs in both the lower and upper parts of the Kuyal'nik Formation, the later can be considered as an analogue of the Akchagylian regional stage, although the uppermost Kuyal'nik layers in the Odessa area correspond probably to the basal layers of the Apsheronian regional stage (Semenenko, 1975a; *Neogenovaya sistema...*, 1986).

In the magnetostratigraphic scale, the Akchagylian base coincides with the Gilbert–Gauss boundary (Trubikhin, 1977; Semenenko and Pevzner, 1979), i.e., with the level of 3.6 Ma. The upper boundary of the stage is at the level of 1.87 Ma slightly above the Olduvai Subchron (Chumakov *et al.*, 1988b). The Akchagylian sediments of the eastern Crimea yield nannofossils referred by Lyul'eva to the interval of NN17–NN18 zones (Semenenko, 1987). Taking these data into consideration, we correlated the Akchagylian regional stage with the Piacenzian and Gelasian stages of the Mediterranean scale, with the upper *Paludina* Beds of the Western Paratethys, and with the Romanian regional stage of the Eastern Paratethys.

At the beginning of the middle Pliocene (initial Akchagylian Age), the Eastern Paratethys consisted of two autonomous Kuyal'nik and Akchagyl basins. The former situated in the northern Black Sea region inherited the brackish-water regime from the preceding Kimmerian basin and became gradually desalinated with time. The Akchagyl basin of the Caspian region was of a semimarine type.

By configuration, the Kuyal'nik basin resembled the Kimmerian one. Occupying the modern Black Sea area, it entered the contemporary land in the southeast to form the Rioni gulf. Its northern part at the site of modern Sea of Azov formed the Kuban' gulf in lower courses of the Kuban' River, and the western part represented the Odessa gulf that communicated with the Azov part of the basin via the Tavriya strait (Eberzin, 1940, Fig. 195).

Salinity of the Kuyal'nik basin was low as it can be inferred from freshwater taxa abundant amid mollusks. This is also evident from composition ostracode assemblage and from absence of foraminifers and nannofossils. The less diverse genera and species of brackish-water molluscan assemblage and their smaller dimensions as compared with the Kimmerian predecessors can be explained by the water desalination and climatic cooling of the Kuyal'nik time (Andrusov, 1923; Eberzin, 1940). Judging from composition of fossils, brief transgressions of the Akchagylian sea into the North Euxinian areas occupied by the Kuyal'nik basin did not influence salinity of the latter.

The Caspian region was occupied by a quite different basin. It was a vast semimarine basin that appeared at the beginning of the Akchagylian Age and stretched northward from the Elburz Mountains for a distance over 2000 km (Andrusov, 1902; Kolesnikov, 1940; Paramonova 1994). The early Akchagylian sea transgression advanced far to the north, east, and west into the past valleys of Volga, Kama, Ural, Amudar'ya, Kura and other rivers. It flooded spacious areas of the North Caspian depression, Aral and Kyzylkum regions, and reached, via Manych and adjacent areas, the Sea of Azov depression.

The early Akchagylian transgression was followed by regression, which resulted in shoaling of the basin and, probably, its insignificant desalination. The next, middle Akchagylian transgression was the maximal one in the entire Akchagylian. The terminal Akchagylian was marked by a significant regression responsible for significant shoaling and desalination of the basin.

Thus, salinity of the Akchagylian sea varied with time. It hardly exceeded 5–9‰ at the beginning of the early Akchagylian, then gradually increasing up to maximum values of 18–19‰ in the central part of the basin (Nevesskaya *et al.*, 1986; Paramonova, 1994). In the late Akchagylian, salinity could be as high as 11–12‰ (Alieva, 1972) in the southern part of the basin and much lower in its northern areas (Paramonova, 1994).

As for the origination of the intense Akchagylian transgression, it seems to have been connected with the waters influx from a vast semimarine basin that had a restricted connection with the Mediterranean Sea. This is evident from composition of mollusks having Mediterranean "roots" (Starobogatov, 1970; Nevesskaya *et al.*, 1986, Paramonova, 1994).

THE NEOGENE–QUATERNARY BOUNDARY

This boundary (*GSSP*, 1985, 1999; 1.8 Ma) is placed slightly above the upper boundary of the Akchagylian regional stage (at the level of 1.87 Ma, after Chumakov, 1993), within the basal part of the Apsheronian regional stage.

CONCLUSION

The suggested Neogene scale of the Eastern Paratethys is based on the thoroughly traced sedimentary succession of all defined regional stages, which elucidates the geological history of this spacious epicontinental basin during the Neogene. Simultaneously, it is difficult

to correlate all the regional stages of the Eastern Paratethys with stages and zones of the International stratigraphic scale, because many of them are lacking zonal assemblages of planktonic groups. In addition, the adequate correlation is hampered by ambiguous interpretation of some stage ranges in the International Mediterranean stratigraphic scale (Berger, 1992; Franseen *et al.*, 1996). Further investigations should be aimed therefore to study distribution of planktonic organic remains and paleomagnetic characteristics of sediments that is necessary for a more reliable correlation of regional sages distinguishable in the Eastern Paratethys with the stages of the International Neogene scale.

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The Early Paleozoic Ministromatolites

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Abstract—In spite of intensive sedimentological and biostratigraphic investigations of ministromatolites, their assemblages systematically studied are those of Precambrian age. Ministromatolites occurred in abundance in the Early Proterozoic and Early Riphean but disappeared later. After the Early Cambrian diversification, they became components of Paleozoic stromatolitic assemblages of many continents, as it is evident from available data on newly discovered Cambrian and Ordovician taxa. Formal genera of the Early Paleozoic ministromatolite assemblage are nearly as diverse as the Early Proterozoic and Early Riphean ones, but they are, however, of an essentially different taxonomic composition. In distinction from the Precambrian taxa, many younger forms are relatively large in size, and some of their formal genera show immature lamination similar to that of thrombolites. The frequent occurrence of stromatite-forming microfossils (particularly of genera that appeared at the Precambrian–Cambrian boundary time) in Cambrian and Ordovician ministromatolites suggests that the formation of the Early Paleozoic ministromatolite assemblage was closely related to the microbial evolution.

Key words: ministromatolites, stromatolitic assemblages, Early Paleozoic, Cambrian, Ordovician, Precambrian, Riphean, Early Proterozoic.

INTRODUCTION

In investigations of microbial sediments, a great attention has been paid to small-sized columnar forms considered as an independent category of stromatolites. Tough they were identified under different names (for detailed review see Raaben, 1998), the term "ministromatolites" introduced by Hofmann and Jackson (1987) is in common usage now.

Ministromatolites are columnar forms 0.2 to 20 mm across. They are defined as an informal unit of uncertain rank in the stromatolite systematics. In essence, this is a supergeneric taxon consisting of many formal genera but not exhausting the diversity of microstromatites representing one of the main morphotypes of stromatolites (Semikhatov and Raaben, 1996; Raaben and Semikhatov, 1996). In the formalized schemes, these morphotypes are represented by high-rank taxa, such as Microstromatiti (Raaben, 1980), Microstromatithi (Raaben and Sinha, 1989), and Ministromatolitophytacea (Makarikhin and Medvedev, 1997), which are subordinate with respect to Stromatoliti Pia. Ministromatolites are some varieties of microstromatites, genera of which are best studied and diverse. Other microstromatites are excluded from consideration in this article, as I have no data on their Early Paleozoic forms.

Owing to a wider size range, ministromatolites go outside the formal taxon Minicolumellida (columnar microstromatites or minicolumellids, Raaben, 1980; Raaben and Sinha, 1989). In practice, however, these terms as well as Pseudogymnosolenacea of Chinese paleontologists, *Asperia*-form and tiny digitate stromatolites are regarded as synonyms equivalent in relation to Proterozoic forms.

As earlier, ministromatolites are now considered to be promising biostratigraphic or lithostratigraphic marker of the Proterozoic time (Raaben, 1980, 1981; Korsakov *et al.*, 1995; Gray, 1984; Liang *et al.*, 1984; Zhu *et al.*, 1987; Grotzinger, 1990; and others). On the other hand, they are favorable objects to study the stromatolite morphogenesis: they are of decisive significance for defining nature (biogenic or inorganic origin) of fossil stromatolitic buildups (Grotzinger, 1990; Raaben, 1998).

Until recently, the study was concentrated almost exclusively on the Precambrian ministromatolites. The common opinion was (and remains to some extent) that this category of stromatolites does not occur stratigraphically higher than the Paleoproterozoic or the lowermost Mesoproterozoic. Ministromatolites are actually very rare in younger Precambrian deposits (Korsakov *et al.*, 1995), but they have been detected in the Cambrian strata (Krylov, 1985) and are obviously frequent components of the Early Paleozoic microbial sediments. This article is the first endeavor to characterize the Early Paleozoic ministromatolite assemblage. It sums up published data concerning Cambrian and Ordovician forms referable to ministromatolites on the base of their size. These forms were described in the 1960s–1970s as columnar or columnar-layered stroma-

Taxonomic composition of the Early Paleozoic ministromatolites

Taxon	Diameter, mm	Occurrence
Cliefdenia fasciculata Werby, 1982	0.3–0.8	Ordovician of S. Australia
Charaulachia zhuravlevae Schenf., 1975	0.3–3	Lower Cambrian of Siberia
Tysseria voronovae Raab., 1998	0.3–3	Lower Cambrian of N. Siberia
Setula recta (gen. et sp. nov.)	1–2	Lower Cambrian of N. Siberia
Turris lenaicus (gen. et sp. nov.)	5–10	Lower Cambrian of N. Siberia
Vetella uschbasica Kryl., 1967	3–5	Lower Cambrian of Kazakhstan
Vetella miritchunica Doln., 1984	5–10	Lower Cambrian of SE Siberia
Vetella ordoviciana (sp. nov.)	3–10	Ordovician of Siberia
Vetella sarfatae Schmitt, 1979	3–15	Lower Cambrian of N. Africa
Igoudinia hemisphaerica Schmitt, 1979	3–20	Lower Cambrian of N. Africa
Neoparmites aptus (gen. et sp. nov.)	2–20	Lower Cambrian of N. Africa
Neoparmites victorius (Sidor.), 1969	3–30	Lower Cambrian of Siberia and N. Africa
Neoparmites nochtuicus (Doln.), 1974	10–20	Lower Cambrian of SE Siberia
Thrombolitina rotunda (gen. et sp. nov.)	5–20	Lower Cambrian of N. Africa
Madiganites lembdadensis Schmitt, 1979	5–25	Lower Cambrian of N. Africa
Glebulella columnaris Masl., 1960 (part.)	10–20	Upper Cambrian of Siberia
Glebulella cavernosa Doln., 1974	5–20	Lower Cambrian of SE Siberia
Columnaefacta minuta Doln., 1974	7–15	Lower Cambrian of SE Siberia
Columnaefacta ilica Kryl., 1975	8–20	Upper Cambrian of SE Siberia
Columnaefacta vulgaris Sidor., 1969	10–20	Lower Cambrian of SE Siberia
Ilicta cf. *composita* Sidor. in Schmitt and Southgate, 1982	3–20	Middle Cambrian of N. Australia
Acaciella angepena Preiss, 1972	1–20	Lower Cambrian of S. Australia
Acaciella cf. *angepena* Preiss, in Schmitt, 1979		Lower Cambrian of N. Africa
Aldania mussoorica Tewari, 1984	15–20	Lower Cambrian of the Lesser Himalayas (India)

Note: In addition to listed taxa, some unnamed forms of the same size have been described and pictured from the Lower Paleozoic of Siberia, North Africa, and South Australia (Luchinina, 1988; Schmitt, 1979; Haslett, 1976) and, what is especially important, from the Lower Cambrian of Western Europe (Dore, 1963).

tolites. These data are supplemented by description of new taxa from the Lower Cambrian and Ordovician deposits of Siberia and North Africa.

Characterizing the Early Paleozoic ministromatolites in general, I should note that the available data on their assemblage composition are far from being complete. As a result of comprehensive paleontological investigation of the Precambrian-Cambrian boundary problem, the best studied ministromatolites are those of the Early Cambrian age. The majority of Early Paleozoic ministromatolites is known from the Lower Cambrian deposits. Thus, the characterized assemblage predominantly reflects distinctive features of Early Cambrian taxa. A few Early Paleozoic forms of a younger age fit well, however, this characterization.

It is noteworthy that ministromatolites, which had almost disappeared by the end of the Precambrian, are proved to occur in the Lower Paleozoic deposits of northern and southern Asia, Western Europe, Africa, and Australia. They had the worldwide distribution and high taxonomic diversity as early as in the Early Cambrian (table).

CHARACTERISTICS OF THE EARLY PALEOZOIC MINISTROMATOLITE ASSEMBLAGE

As compared to the post-Riphean stromatolites impoverished in general, the Early Paleozoic ministromatolite assemblage seems to be rather diverse. In addition to nameless forms, it contains more than 20 formal species of Cambrian and Ordovician age belonging to 15 formal genera (see table). The species listed in the table are within the size limits characteristic of ministromatolites: diameter of their columns varies from parts of millimeter to 2 cm. For the purpose of convenience, the species may be divided into two groupments. The first groupment includes forms less than 1 cm across, which fit diagnosis of the supergeneric taxon *Minicolumellida*. The groupment consists of eight formal species representing six genera. The second group-

ment is composed of ministromatolites larger in size. It is easy to notice that the relatively large-sized ministromatolites represent two thirds of the listed species and more than a half of the Early Paleozoic genera, whereas the pre-Riphean and Early Riphean ministromatolites correspond almost exclusively to miniature minicolumellids. The gap in size between microstromatites and "usual" macroscopic stromatolites, which is apparent in the Precambrian forms, becomes unnoticeable in the Early Paleozoic ones.

All ministromatolites of the first groupment, i.e., minicolumellids, belong to genera known so far from the Lower Paleozoic. Many genera, such as *Charaulakhia* Schenf., *Tysseria* Raab., *Setula* gen. nov., and *Turris* gen. nov., are confined to the Lower Cambrian strata. *Klifdenia* Werby occurs only in the Ordovician. *Vetella* Kryl. was found in Cambrian and Ordovician deposits, being represented there by different species. The ministromatolites of this groupment are characterized by distinctly separated thin columns, laminated structure, and inherited arches. In spite of the common features, the assemblage of *Vetella uschbasica* Kryl., *V. ordovicea* sp. nov., *Charaulakhia zhuravlevae* Schenf., *Tysseria voronovae* Raab., *Klifdenia fasciculata* Werby, *Setula recta* gen. nov., and *Turris alderis* sp. nov. shows a great morphological variability, and every taxon, at both the generic and specific levels, is easily recognizable. All these genera are also well distinguishable from the pre-Riphean and Early Riphean minicolumellids, none of which survived to the Early Paleozoic.

The second groupment of larger ministromatolites partly consists of the Lower Paleozoic genera and partly of those inherited from the Riphean and Vendian. The former are represented by *Madiganites lembdadensis* Schmitt, *Thrombolitina rotunda* sp. nov., *Glebulella cavernosa* Doln., *G. columnaris* Masl., *Igoudinia hemisphaerica* Schmitt., *Vetella sarfatiae* Schmitt., *Ilicta* cf. *composita* Sidorov, *Neoparmites aptus* sp. nov., *N. victorius* (Sidor.), and *N. nochtuicus* (Doln.). These are characterized by polymorphic columns with irregular branching, and thus are similar to columnar branching stromatolites of the Illictid supergroup.

With their polymorphic columns and buildups, these representatives of different genera have some principal morphological features in common. The columns are extremely changeable in diameter and height. Irregularly located branching of the α-, β-, or γ-parallel types vary to sharply divergent and horseshoe-shaped. The columns are irregularly arranged; bush-like or any regular fascicular buildups are untypical of all these forms. The forms under consideration also show a common structural feature, which can be defined as an immature lamination, i.e., the laminated structure of their columns, if any, is poorly pronounced. Boundaries between laminae can be identified occasionally, at large and unequal intervals; dark laminae are seldom distinguishable from light ones, and there is no regular frequent alternation of them.

The features in common mentioned above are combined with some differences of variable degree. For instance, *Thrombolitina rotunda* and *Madiganites lembdadensis* do not show any signs of lamination in their columns and differ from each other in microstructure of the fine carbonate matter. Most likely, both forms should be assigned to a single genus, though *Thrombolitina rotunda* cannot be attributed to the genus *Madiganites* Walt., because the Australian type form of the latter is a rather large and distinctly laminated stromatolite. The generic affinity of *M. lembdadensis* Schmitt should be revised better by authors of the genus and species.

The other forms demonstrate some signs of immature laminated structure. Both species of the genus *Glebutella* Masl. are similar in appearance to *Th. rotunda* and *M. lembdadensis*, as they are lacking bridges and have predominantly clotted texture of carbonate material. Bridges typical of other forms increase polymorphism of *Neoparmites, Igoudinia*, and *Vetella sarfatiae* buildups similar in general habit. The last form noticeably differs from the *Vetella* Kryl. type form (Bertrand-Sarfati, 1981).

Finally, a part of Lower Paleozoic ministromatolites is represented by genera inherited from the Precambrian. These are representative of genera *Columnaefacta* Korol., *Acaciella* Walt., and *Aldania* Kryl. listed in the table. They mostly have subcylindrical subvertical columns with well-pronounced layered structure and banded or lamellar texture. From the type forms of the above genera, they differ in smaller size, microstructural peculiarities, and details of marginal structure.

Summing up, it is necessary to note that the representative Early Paleozoic assemblage of ministromatolites is separated from older Early Proterozoic and Early Riphean diverse assemblages by a considerable time span having no generic or species affinities. It contains only scarce representatives of genera, which are not older in age than the Middle Riphean. Although these are the smallest columnar forms of genera, they belong to the groupment of larger ministromatolites. The Early Paleozoic assemblage also includes a number of undoubtedly true minicolumellids representing up to one third of the known formal species of the assemblage.

The most remarkable and characteristic components of the assemblage are larger ministromatolites with the immature laminated structure. Because of unusual formation of their columns and buildups, they resemble nonlaminated microbial sediments and can be regarded as peculiar columnar minithrombolites. Owing to these forms, the Early Paleozoic assemblage of ministromatolites sharply differs from the Proterozoic ones. The ministromatolites in question reveal interregional and intercontinental distribution patterns.

The most widespread genera and species of the Early Paleozoic assemblage of ministromatolites are *Charaulakhia zhuravlevae* Schenf. occurring in northern and southeastern Siberia (Schenfil', 1975), *Neoparmites victorius* (Sidor.) and *Vetella* Kryl. found in Siberia and North Africa (Semikhatov, 1977; Schmitt, 1979), and the Early Cambrian *Aldania* characteristic of Tommotian phosphate rocks in the Lesser Himalayas, India (Tevari, 1983), and in the Lesser Karatau Ridge, Kazakhstan.

Well-preserved remains of laminae-forming microfossils were found in ministromatolite columns of small and larger sizes. Such microfossils are known in *Cliefdenia fasciculata* Werby (*Girvanella*), *Tysseria voronovae* Raab., *Igoudinia hemisphaerica* Schmitt (*Epiphyton, Girvanella,* and *Renalcis*), and in some unnamed ministromatolites from the Lower Cambrian of France and from the Ordovician of Siberia (Dore, 1963; Werby, 1982; Schmitt, 1979; Raaben, 1998; Luchinina, 1988). The noteworthy fact is that these microfossils occur more frequently in the Early Paleozoic ministromatolites than in older counterparts.

DESCRIPTION OF NEW TAXA

Neoparmites (gen. nov.).

Type species: *N. aptus* (sp. nov.), Lie-de-Vin Group, Anti-Atlas, Morocco.

Diagnosis. Ministromatolites of larger size with occasionally uniting columns of variable diameter, which form irregularly branching buildups up to 15–20 cm high and more. Columns with multidirectional axes show whimsical configuration inflated and constricted asymmetrically. Margins are either almost smooth but wall-less, or uneven but without sharp cusps. Columns are variably spaced and locally united by long thick horizontal connecting bridges, while fine bridges are untypical. Divergent bifurcations are occasionally horseshoe-shaped. Lamination is immature and indistinct, dark- and light-colored layers are poorly or not differentiated; arches are of non-inherited type.

Comparison. In outcrops and thin sections, buildups of *Neoparmites* resemble those of *Parmites* Raab., *Igoudinia* Schmitt, and *Vetella sarfatiae* Schmitt. *Neoparmites* has immature laminated structure like two the latter forms, but in distinction it is composed of relatively high, narrow, and slightly curved columns. Small frequently uniting columns represent the only feature in common with the *Parmites* forms. In distinction from *Neoparmites,* columns of Riphean *Parmites* Raab. are regularly widening upward, having discontinuous walls or denticulate margins and perfectly developed lamination with inherited arches; their arrangement in branching buildups is radial.

Composition. In addition to the *Neoparmites* type form, I attribute to the genus *N. victorius* (Sidorov) and *N. nochtuicus* (Doln.), which were previously referred to *Parmites* Raab. However, the distinctive features of these forms do not fit the diagnosis of the latter.

Occurrence and age: Anti-Atlas, Morocco, southeastern Siberia, Lower Cambrian.

Neoparmites aptus (sp. nov.).

Plate 1, fig. 3.

Holotype: GIN RAN, no. 4866/164 (specimen no. 164/str.), middle horizons of the Lie-de-Vin Group, Anti-Atlas, Tiout area, Morocco.

Description. Ministromatolite buildups randomly occurring in brick-pink dolomitized limestones 12–15 m thick are distinguishable owing to their lighter coloration. The buildups of irregular shape are composed of subvertical and variously inclined, high (up to 10 cm) and relatively narrow columns of variable diameter (from 3–4 to 15–16 mm), which are asymmetrically inflated and constricted. Bifurcations are divergent, frequently horseshoe-shaped. The column surface is noticeably curved, either smooth without being enveloped or uneven without sharp cusps. Neighboring columns are occasionally united, whereas widely spaced ones are connected with thick long horizontal bridges; small frequent bridges are absent.

The internal lamination is indistinct. Dark and light laminae are uniformly composed of microcrystalline carbonate with scattered grains of 0.03–0.05 mm in size. The lamina boundaries are usually discontinuous, spaced at different intervals, and weakly ferruginate in places. Arches are of non-inherited type.

Comparison. Among all *Neoparmites* forms (previously attributed to *Parmites* Raab.), *N. nochtuicus* (Doln.) is distinct because of fine grumous texture of all poorly distinguishable laminae, while *N. victorius* (Sidor.) locally reveals slightly differentiated dark and light laminae. Perfect description of these forms was published by their discoverers (Dol'nik, 1974; Krylov *et al.*, 1969).

Material: seven specimens (lump samples and thin sections) from the Tiout area.

Occurrence: as that of the holotype, Lower Cambrian.

Genus *Thrombolitina* (gen. nov.).

Type species: *T. rotunda* (sp. nov.), Lower Cambrian of the Higher Atlas, Morocco.

Diagnosis. According to column size, these are larger ministromatolites with nonlaminated structure that is untypical of true stromatolites. Configuration and arrangement of columns with multidirectional axes are variable. Column margins are lacking walls and sharp cusps. Connecting layers between columns are not developed. Lamination is indistinct, but some zoning of microstructural elements can be observed locally.

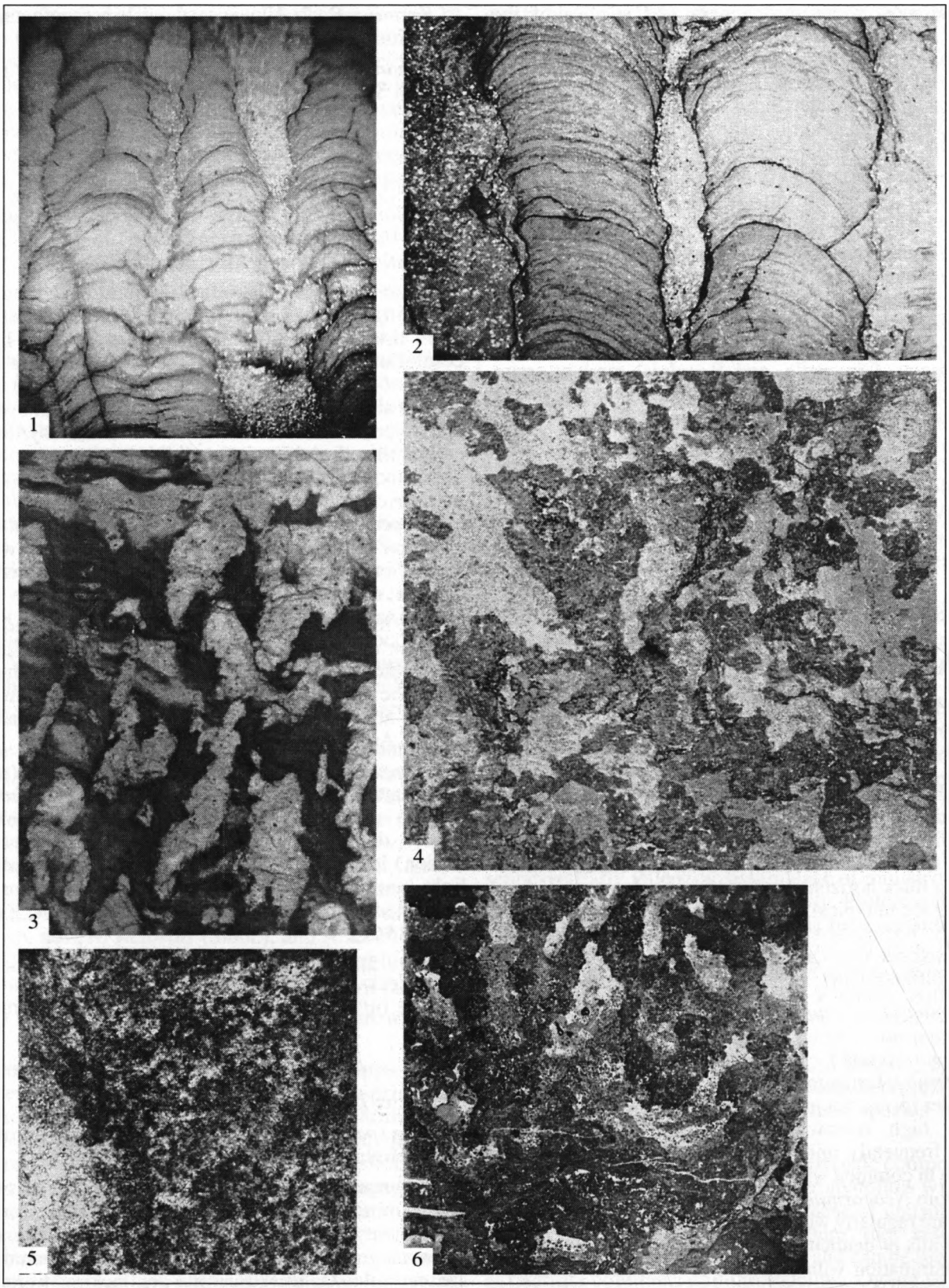

Plate 1. Buildups, columns and structure of ministromatolites:
(1, 2) *Turris alderis* sp. nov.; (3) *Neoparmites aptus* sp. nov.; (4, 5) *Thrombolitina rotunda* sp. nov., holotypes; (6) *Madiganites lembdadensis* Schmitt (specimen no. 218181, oued Lembdad); (except for fig. 3 of polished section all other are pictured from thin sections; scale bars are equal to 5 mm).

Comparison. The new genus *Thrombolitina* differs from all other genera of Early Paleozoic ministromatolites owing to nonlaminated structure.

Composition: the type species.

Remarks. Madiganites lembdadensis Schmitt columns of the same structure may be also referred to this genus.

Occurrence: as that of the type species.

Species *Thrombolitina rotunda* (sp. nov.).

Plate 1, figs. 4 and 5.

Holotype: GIN RAN no. 4866/216 (specimen no. 219/str.), Lower Cambrian of the Ounein area, oued Lembdad, Higher Atlas.

Description. The buildups form slightly convex bioherms 10–15 cm high and resemble "cellular thrombolites" reproduced by Aitkin (1967). Columns are 5 to 20 mm across and 5 to 30 mm high, variable and irregular in shape, frequently tuberoid. Neighboring columns frequently coalesce, but bridges are absent. There are no walls or sharp cusps in the column margins curved irregularly. Instead of lamination, there is seen irregular zoning of microstructural elements. The microstructure is finely globular, with scattered elements sized 0.03–0.04 mm.

Comparison. New species differs from *Madiganites lembdadensis* by its larger size and less frequent distribution of globular elements.

Material: three specimens from the type area, eight thin sections.

Occurrence: Lower Cambrian of the Higher Atlas, oued Lembdad of Morocco.

Genus *Turris* (gen. nov.).

Type species: *T. alderis* sp. nov., Tyusser Formation of the Kharaulakh Ridge, Creek Al'derkhai, Lena River basin.

Diagnosis. Ministromatolites having parallel columns from 5 or 6 to 10 mm in diameter that is considerably lesser than their height. Straight, subcylindrical, vertical columns reveal rare branching. The column margins are wall-less and bear angular cusps. Connecting layers between irregularly arranged columns are absent. Structure is distinctly laminated.

Comparison. The larger column size differs the genus from other minicolumellids found in the same formation or in different Lower Cambrian and Ordovician subdivisions, and also from the Proterozoic parallel-columnar ministromatolites with distinctly separated columns (*Minicolumella chauhana* Raab., *M. barmenae* Raab., and *Longicolumella formosa* Liang.). In distinction from small columns of genera *Jurusania* Kryl., *Aldania* Kryl., and *Columnaefacta* Korol., it is lacking any connecting layers between columns.

Composition: the type species.

Occurrence: as that of the type species, Lower Cambrian.

Species *Turris alderis* (sp. nov.).

Plate 1, figs. 1 and 2.

Holotype: GIN RAN no. 4866/26 (specimen no. B-79-26 of the Missarzhevskii collection), Tyusser Formation, Kharaulakh Ridge, Creek Al'derkhai, Lena River basin.

Description. Vertical subcylindrical columns are arranged in parallel. Their diameter is 5–7 mm in average but may be as great as 9 or 10 mm; the height is up to 5–7 cm. Uneven column margins bear small and large angular cusps. Arches vary in form from gently convex to subspherical, being frequently asymmetrical. Branching is extremely rare, and single bifurcations are of the α-parallel type. Cross sections of columns are frequently elongate in one direction. Longer diameters are two or three times larger than the short ones. Intercolumnar spaces are either equal or several times greater than the column diameters. Lamination is distinct, fine and platy. Grayish micrite layers are 0.02–0.06 mm thick, with slightly ferruginate and frequently stylolitic surfaces.

Comparison. The only species of the genus is known.

Material: eight thin sections in collections of V.V. Missarzhevskii and L.G. Voronova.

Occurrence: Lower Cambrian of the Kharaulakh Ridge.

Genus *Setula* (gen. nov.).

Type species: *S. recta*, Tyusser Formation of the Kharaulakh Ridge, northern Siberia.

Diagnosis. Fine high subcylindrical columns 1–3 mm across, occasionally with slightly divergent or parallel bifurcations. Their uneven margins bear nonuniformly arranged cusps and cavities of irregular shape. Columns are wallless, having no bridges and connecting layers of any type. Columns are thick-laminated, showing slightly convex arches.

Comparison. Setula gen. nov. resembles *Tysseria* Raab. in size and shape of straight cylindrical isolated columns and differs from the latter by uneven contours of columns, longer distance between them, bifurcation type, and thick laminae.

Composition: the type species.

Occurrence: as that of the type species.

Species *Setula recta* (sp. nov.).

Plate 2, figs. 1 and 2.

Holotype: GIN RAN no. 4866/29 (specimen no. B79/29 of Missarzhevskii collection), lowermost Tyusser Formation of the Kharaulakh Ridge.

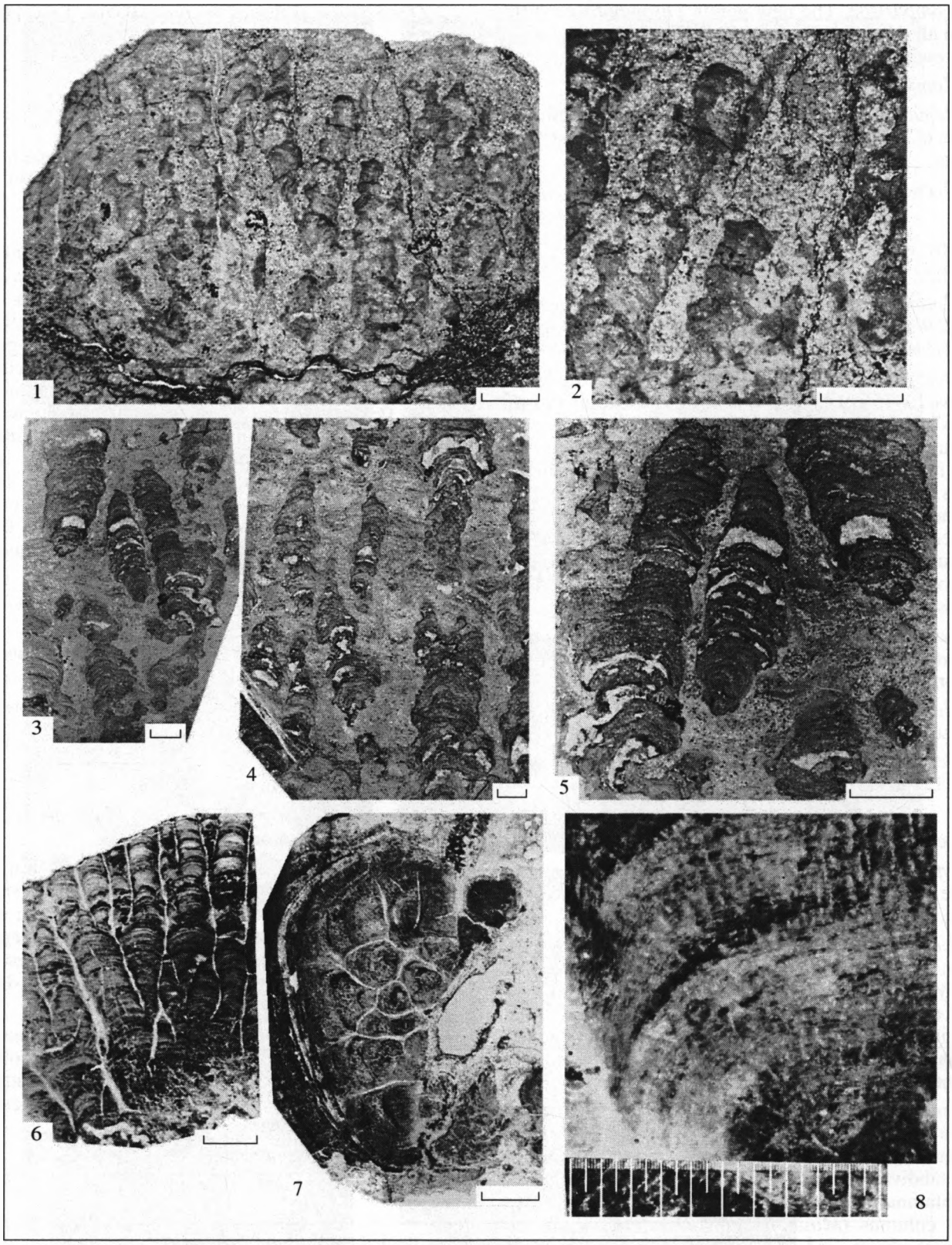

Plate 2. Buildups, columns and structure of ministromatolites:
(1, 2) *Setula recta* sp. nov.; (3–5) *Vetella ordoviciana*, holotypes; (6–8) *Tysseria voronovae* Raab., (6, 8) holotypes, (7) specimen no. B-70/666, cross section of bioherm (all pictures from thin sections, scale bars are equal to 5 mm for figs. 1–7 and to 1 mm graduated by 0.05 mm for fig. 8).

Description. In groups of thin columns not more than 1 or 2 mm across and 1 or 2 cm high in general, some columns are up to 3 cm high. Columns are occasionally ramified, displaying slightly divergent or parallel bifurcations. Margins of cylindrical columns with straight axes have whimsical irregularities. Spaces between columns are usually lesser than their diameter, but sometimes they are 3 to 4 mm wide. Neither bridges between columns nor general connecting layers are observable. Column margins are non-enveloped. Thick (0.5–1.0 mm) lamination is not distinct everywhere. Arches are convex and low. When well-preserved, the lamination is fine-cellular, with round light "windows" seen in grayish micrite. Laminae are composed mostly of grayish structureless micrite with lighter and darker stains.

Comparison: the type species.

Material: the holotype.

Occurrence: the lowermost Cambrian of the Kharaulakh Ridge.

Genus *Vetella* Kryl. 1967.

Species *Vetella ordoviciana* sp. nov.

Plate 2, figs. 3–7.

Holotype: GIN RAN, no. 4866/601 from collection of M.A. Semikhatov, Ordovician of Siberia.

Description. Subcylindrical uneven columns 4–10 mm across and 1–7 cm high. Straight and curved columns form high vertical or inclined buildups of fascicular type, in which the irregular knotty divergent bifurcations are visible. Buildups look like thin tree sprigs, as it is emphasized in the genus name (Krylov, 1967, p. 58). Two or more branches of different size diverge from columns at different angles. They may produce secondary branches or have fingerlike terminations. Columns lacking connecting bridges are variably spaced from each other. Their margins bear bumps and ridges but no sharp cusps; enveloping is developed locally. Lamination is distinct, and crimped arches of incomplete inheritance are occasionally present. Laminae (0.7–0.9 mm thick) are composed of fine-grained gray carbonate darker colored near their upper boundaries. Laminae are locally separated by thin intervals of scattered black dusty particles. Columns and individual laminae frequently include grains of white crystalline calcite responsible for the "fenestral" textural appearance.

Comparison. The new species is similar to the type one in morphology and size of buildups, but its lamellar texture differs it from *V. uschbasica* Kryl. and *V. miritchunica* Doln., both having the well-pronounced banded texture. In distinction from this species, *V. sarfatiae* Schmitt has characteristic radial elements and some other morphological features, e.g., the abundant connecting bridges (Schmitt, 1979).

Material: the type specimen (one lump and more than 20 thin and polished sections).

Occurrence and age: Ordovician of Siberia.

Genus *Tysseria* Raaben, 1998.

Type species: Tysseria voronovae Raab. named after the eponymous formation of the Kharaulakh Ridge.

Diagnosis. Thin even cylindrical and narrow-conical columns less than 5 mm across and up to several centimeters high. Because of branching, they form particular buildups (fascicles), which may be ramified repeatedly. One of characteristic features is a compact arrangement of the fascicles: the columns are closely spaced but distinctly separated and seldom coalescent. Bridges are absent. Column margins are smooth but non-enveloped. Their structure is distinctly laminated, with obviously inherited convex arches. When well-preserved, laminae show radial and layered textural elements.

Comparison. Tysseria Raab. belongs to the true minicolumellids. It is distinguished from the majority of their Precambrian genera by distinctly separated columns and absence of bridges. In distinction from non-fascicular buildups of *Longicolumella* Qui et Zhang, *Minglingella* Xiao, and *Minicolumella* Raab., the genus exhibits repeatedly ramified compact fascicles. The closely spaced columns differ it from the Early Paleozoic genera of comparable size (*Vetella* Kryl. and *Setula* gen. nov.).

Remarks. A brief characteristics of *Tysseria* and description of its type species were published soon after identification of this taxon (Raaben, 1998). The correct diagnosis of the genus and more detailed description of its species are presented here to supplement information on new Early Paleozoic ministromatolite taxa.

Composition: the type species.

Occurrence and age: as those of the type species, Lower Cambrian.

Species *Tysseria voronovae* Raab. 1998.

T. voronovae, Raaben, 1998, pp. 156–158.

Plate 2, figs. 6–8.

Holotype. GIN RAN, no. 4866/615 (specimen no. B70/66) of the Tyusser Formation of the Kharaulakh Ridge, Creek Al'derkhai.

Description. The *Tysseria* buildups occur in light-colored limestone enclosing brightly green glauconite grains and hyolithid shells. They form crust-type bodies 5 or 6 cm long and up to 3 cm thick, as well as miniature bioherms 0.5–1.5 cm across. The buildups and their constituent columns are closely spaced. Cylindrical or narrow-conical columns vary in size: from 0.3 to 3.0 mm (frequently 1 or 2 mm) in diameter and from 2 to 20 mm in height. Cross sections of columns are rounded-polygonal, margins are very smooth, walls are absent. The column axes are normal relative to the substrate or slightly curved. Frequent, predominantly repeated branching with narrow β-parallel bifurcations is typical. Intervals between columns are narrow (less than 0.15 mm). The buildups represent compact fasci-

cles. The columns are distinctly separated, seldom coalescent, and lacking connecting bridges. Laminae of variable thickness are distinct, and gently convex inherited arches are characteristic. In well-preserved areas, there is visible a non-uniform texture of alternating layered-fibrous (0.01–0.1 mm) and radial-fibrous (0.1–0.6 mm) laminae. The former are completely composed of sheaths of filamentous *Gyrvanella* forms, while the latter exhibit the radial positioning of casts of *Epiphyton* filaments, some of which penetrate into overlying layers, and of *Renalcis* form set in the fine-grained calcite.

Comparison. The only species of the genus is known.

Material: the type specimen and thin sections B-70-66 and A-K from the same outcrop.

Occurrence: Tyusser Formation, Creek Al'derkhai, Lena River basin, northern Siberia; Lower Cambrian.

CONCLUSION

Ministromatolites became widespread again in the Early Paleozoic and were diverse as early as in the earliest Cambrian. The quantity of genera, which approximated zero in the terminal Precambrian, increased in the Early Cambrian up to the value comparable with that characterizing the diverse Early Riphean and Paleoproterozoic assemblages. The formal quantity index seems less important than the qualitative diversity of the Early Paleozoic ministromatolites, which show a wide size spectrum and very different types of column structure.

On the one hand, the Early Paleozoic assemblage includes ministromatolites that are similar in size range and column structures to the Paleoproterozoic and Early Riphean minicolumellids and pseudogymnosolenids, though they are represented by newly appeared genera. On the other hand, the assemblage also includes larger ministromatolites, similar to the smallest form-species of some transitional Riphean–Vendian genera of columnar-branching stromatolites. The third, especially remarkable part of the assemblage is represented by larger ministromatolites with peculiar indistinct internal structures of columns. In their specific immature lamination, they resemble thrombolites. None of similar genera is known from the Precambrian deposits.

In terms of biostratigraphy, ministromatolites displaying the thrombolite type of columnar structures are of prime interest at present. In perspective, the Early Paleozoic minicolumellid genera may serve as important fossils owing to their readily recognizable features. However, these genera are considered now as endemics, and their biostratigraphic significance can be elucidated after further investigations.

Ministromatolites are often used to solve general problems of stromatolite morphogenesis, and therefore their Early Paleozoic forms worth a special attention. Columns of Cambrian and Ordovician miniforms frequently include lamina-forming microfossils. This discards the idea of an inorganic origin of all or most ministromatolites. The known microbial remains are dominated by genera appeared at the Precambrian–Cambrian transitional time. This implies a possible relation between the formation of the Early Paleozoic ministromatolite assemblage and evolutionary changes in the world of microbes.

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Cyclostratigraphy of Upper Paleozoic Terrigenous Deposits in the Taimyr Peninsula

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Abstract—Combination of sedimentological and cyclostratigraphic methods is used to depict for the first time the relative sea-level fluctuations characterizing a series of sections of Upper Paleozoic terrigenous deposits in the Taimyr Peninsula. As a result, seven transgression–regression cycles of the fifth order (magnacycles) are distinguished. According to their position in sections, paleontological characteristic, and changes in lithology and facies types, the cycles are identifiable throughout the region. Thus, the established magnacycles can be regarded as natural regional geohistoric units useful for elaboration of a new stratigraphic scheme for the Upper Paleozoic in the Taimyr Peninsula.

Key words: Upper Paleozoic, sea-level fluctuations, Taimyr Peninsula, regional correlation, terrigenous sequence, cyclostratigraphy.

INTRODUCTION

Paleontological studies by E.M. Lyutkevich, O.V. Lobanova, G.P. Sosipatrova, V.I. Ustritskii, G.E. Chernyak, N.A. Shvedov, and O.L. Einor laid the groundwork for regional stratigraphy of Upper Paleozoic of the Taimyr Peninsula. Based on stratigraphic distribution of foraminifers, brachiopods, bivalves, and plant remains in the sections, the Makarov, Turuza, Byrranga, Sokolinyi, Baikura, and Chernoyarsk regional horizons are distinguished in the study region (Shvedov *et al.*, 1960). Later on, their stratigraphic succession (Table 1) was refined by biostratigraphic methods. Ustritskii (1984) subdivided the Makarov Horizon into the Kholodnyi and Zheleznyi horizons (*Resheniya...*, 1982), and the Baikura Horizon into the Belosnezhka and Tsvetochnyi horizons. The age interpretation of the Byrranga, Sokolinyi, and Baikura horizons was subjected to repeated changes. This seems to indicate uncertain stratigraphic ranges of the horizons rather than the age revision of paleontological assemblages. As satisfactory stratotypes for many horizons had not been established, the outdated paleontological identifications (carried out mainly in the 1950s–1960s) hampered approval of the regional Upper Paleozoic stratigraphic scheme for the Taimyr Peninsula by the Interdepartmental Stratigraphic Committee.

In addition to above problems, the complexity with respect to regional Upper Paleozoic stratigraphy of the Taimyr Peninsula is related to the lateral compositional changeability of polyfacies deposits and interrelated changes in ecological assemblages of organic remains. This peculiarity is especially characteristic of the Baikura Horizon sections, rocks of which yield marine fauna on the east and terrestrial flora on the west. Moreover, beds with marine fauna important for dating are rare and irregularly distributed throughout the sections, being often spaced from each other by considerable intervals (hundreds of meters). This is another complexity in application of biostratigraphic criteria for the regional correlation. A possibility to use cyclostratigraphic criteria for upgrading the regional scheme seems to be promising in this situation. Such an approach takes into account the relative synchronism of high-order cyclothems within vast areas, which is controlled by regional (sometimes planetary) tectonic movements, eustatic sea-level fluctuations, and climatic changes (Predtechenskii, 1984). Unfortunately, attempts to substantiate by cyclostratigraphic methods the ranges of local and regional units in the Taimyr Peninsula (Gramberg *et al.*, 1960; Ustritskii and Chernyak, 1963) were not very successful, since sedimentary cycles distinguishable in particular sections had not been traced spatially, and their correlation potential hence remained unknown.

MATERIALS

Lithological and paleontological characteristics of representative sections of Upper Paleozoic deposits in the Taimyr Peninsula are used as a basis for this work (Figs. 1, 2). Analyzing in bed-by-bed manner the natural exposures and borehole sections, I depicted stratigraphic columns for the Yenisei area of western Taimyr, the Pyasina River lower courses, the Tareya River basin, and the area of the Lake Taimyr northwestern shore. Paleontological materials characterizing the sections were studied by N.G. Verbitskaya (flora), V.G. Ganelin (brachiopods), G.P. Pronina (smaller for-

Table 1. Elaboration history of the Upper Paleozoic regional stratigraphic scheme for the Taimyr Peninsula

System	Series	Stage	Shvedov, Ustritskii, Chernyak *et al.* (1960)		Ustritskii and Chernyak (1963)		Gramberg, Preobrazhenskaya, and Ustritskii (1978)		Ustritskii (1984)		Solomina and Preobrazhenskaya (1993)
			Subseries	Horizon	Horizon	Subhorizon	Horizon	Subhorizon	Horizon		Horizon
Permian	Upper	Tatarian	Upper	Tuff–lava Formation					Zverin		Zverin
				Chernoyarsk	Chernoyarsk		Chernoyarsk		Chernoyarsk		Chernoyarsk
		Kazanian			Baikura	Upper	Baikura	Upper Baikura	Tsvetochnyi		Tsvetochny; Belosnezhka
		Ufimian	Lower	Baikura		Lower		Lower Baikura			
					Sokolinyi				Belosnezhka		Sokolinyi
	Lower	Kungurian	Upper	Sokolinyi	Byrranga		Sokolinyi		Sokolinyi		
		Artinskian		Byrranga			Byrranga		Byrranga		Byrranga
		Sakmarian	Lower	Turuza	Turuza		Turuza	Upper Turuza	Turuza	Upper Turuza Subhorizon	Upper Turuza Subhorizon
		Asselian									
Carboniferous	Upper	Gzhelian		Makarov				Lower Turuza		Lower Turuza Subhorizon	
		Kasimovian									
	Middle	Moscovian			Makarov	Lower	Makarov	Upper Makarov	Zheleznyi		
		Bashkirian				Upper		Lower Makarov	Kholodnyi		

aminifers), A.S. Byakov (marine bivalves), and O.A. Betekhtina (non-marine bivalves). In addition, I used descriptions of sections and paleontological data available from publications (Gramberg *et al.*, 1960; Ivanov, 1960; Migai, 1954; Solomina and Preobrazhenskaya, 1993; Ustritskii and Chernyak, 1963) and unpublished materials characterizing the Uboinaya River right bank (deposited by Pogrebitskii *et al.*, 1955) and Chernokhrebetnaya River upper courses (deposited by Zakharov, 1964, and by Bezzubtsev *et al.*, 1979).

METHODS

The problem of distinguishing natural regional geohistoric units, which recorded evolution of sedimentation in the Late Paleozoic basin of Taimyr Peninsula, can be solved using criteria of facies lithology and cyclostratigraphic approach. The multiple-order sedimentary cycles are distinguishable in sections of Upper Proterozoic deposits based on successive changes in their grain size and bed thickness, presence of coal seams, and on lithological and facies variability of rocks complexes (Shishlov and Verbitskaya, 1990; Shishlov *et al.*, 1997). Cycles of the fifth order, the so-called magnacycles, are of particular interest for regional correlation. They are distinguishable in sea-level fluctuation curves depicted for all the sections mentioned above (Fig. 2). When plotting these curves, I used the rock typification based on a steady combination of interrelated genetic parameters (composition, grain sizing, textures, taphocoenoses, con-

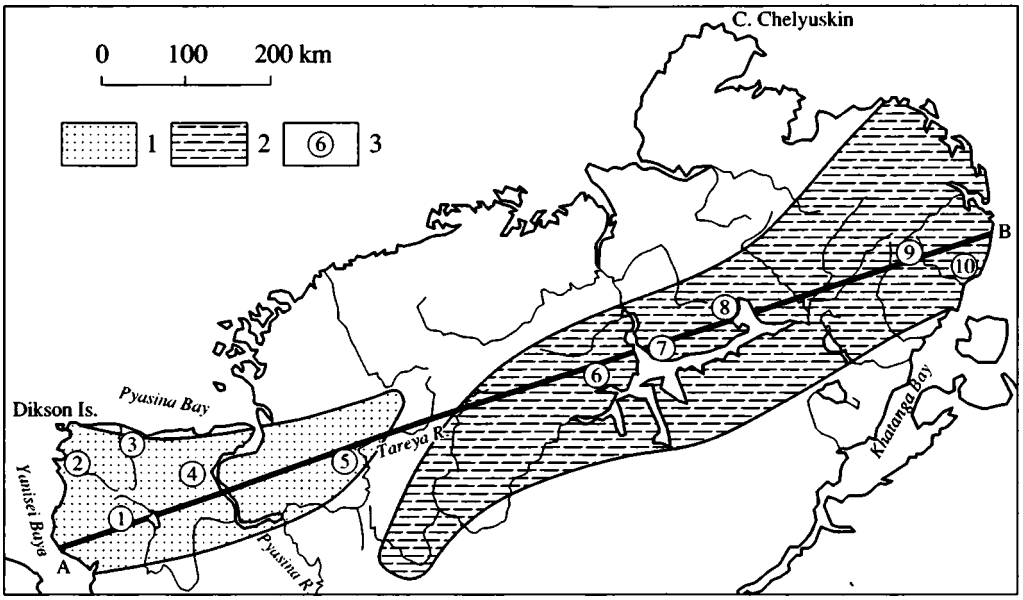

Fig. 1. Upper Paleozoic terrigenous deposits in the West (1) and East (2) Taimyr depressions with shown localities of analyzed sections (3). Encircled section numbers denote the following localities: (1) Syradasai River basin, (2) Efremov River lower courses (after Ivanov, 1960), (3) Uboinaya River right bank (after Pogrebitskii *et al.*, 1955), (4) Pyasina River lower courses, (5) Tareya River basin, (6) Ledyanaya Bay area, (7) the area of the Nestor Kulik Bay: str. Belosnezhka (Solomina, Preobrazhenskaya, 1993), Zayach'ya River, (8) the area of Yam-Baikur Bay: Tsvetochnaya, Sokolinaya, and Severnaya rivers (after Ustritskii and Chernyak, 1963), (9) Chernokhrebetnaya River upper courses (after Zakharov, 1964; Bezzubtsev *et al.*, 1979), (10) Chernokhrebetnaya River lower courses and Tsvetkov River in the Cape Tsvetkov area (after Migai, 1954; Gramberg *et al.*, 1960); (A–B) line of lithological–facies profile shown in Fig. 3.

cretions, etc.) and the reconstruction of sedimentation conditions. As a result, eight lithological–facies complexes have been distinguished in Upper Paleozoic deposits of the Taimyr Peninsula.

(1) *Argillaceous–silty deposits of a deep open shelf (below the wave base)*; these are mudstone, clayey siltstone (dominant), alternating lenticular (usually with indistinct boundaries) siltstone beds, and single thin (less than 1 m) interlayers of silty high-calcareous sandstone. The rocks are of gray color, often calcareous, with rare Ca-carbonate concretions and abundant fine impregnation and spherical nodules of sulfides. Identifiable remains of marine fauna are rare, vertical fucoids are found, microscopic plant remains are missing, in places a high concentration of fine-dispersed organic material is observed.

(2) *Sandy–silty deposits of a shallow-water (above the wave base) open shelf*: distinct lenticular-banded siltstone beds (dominant), members (up to 10 m thick) of fine-grained calcareous sandstone, lenticular (1–10 cm) accumulations of shell detritus and small pebbles of clayey–silty rocks (tempestites), and flat-bedded clayey siltstone. The rocks contain abundant Ca-carbonate and sulfide nodules. Horizons with abundant marine fauna (foraminifers, crinoids, brachiopods, bivalves), rare plant slime, and various invertebrate ichnofossils (*Zoophycos* assemblage) are common.

(3) *Silty–sandy deposits of the bar belt*: distinct lenticular–banded alternation of siltstone (coarse-grained varieties are dominant), and frequent members (5–10 m) of fine-grained calcareous sandstone. Mg-Ca-carbonate concretions, ichnofossils (*Cruziana* assemblage), accumulations of plant detritus, and rare identifiable remains of flora and marine fauna are typical.

(4) *Sandy–silty, slightly carbonaceous deposits of the intertidal and supratidal areas (tidal marshes)*: complex includes lenticular-banded and wavy alternations of siltstone beds, thick (15–20 m) members of inequigranular (from fine- to coarse-grained) sandstone, and individual thin (0.1–0.4 m) non-persistent coal seams. The rocks bear Mg-Ca-Fe-carbonate concretions, plant remains (identifiable included), small rhizocretions buried in situ, individual shells of euryhaline bivalves, and invertebrate ichnofossils.

(5) *Sandy–silty coal-bearing productive deposits of lagoons with intensely swamped coasts*: typical are gray flat-bedded mudstone and siltstone (often carbonaceous); wavy alternations of clayey, fine- to coarse-grained siltstone beds (dominate in the section); members (5–10 m) of inequigranular sandstone (in places with lenticular accumulations of pebble and gravel); and numerous persistent coal seams, often reaching the minable thickness (0.7–12.5 m). The rocks contain Fe-carbonate concretions, abundant and diverse plant remains, and individual small shells of brackish-water bivalves.

(6) *Conglomerates and sandy deltaic deposits*: complex is composed of thick (up to 25 m) members of inequigranular (mainly coarse-grained) sandstone with interlayers of gritstone and conglomerate, indistinctly

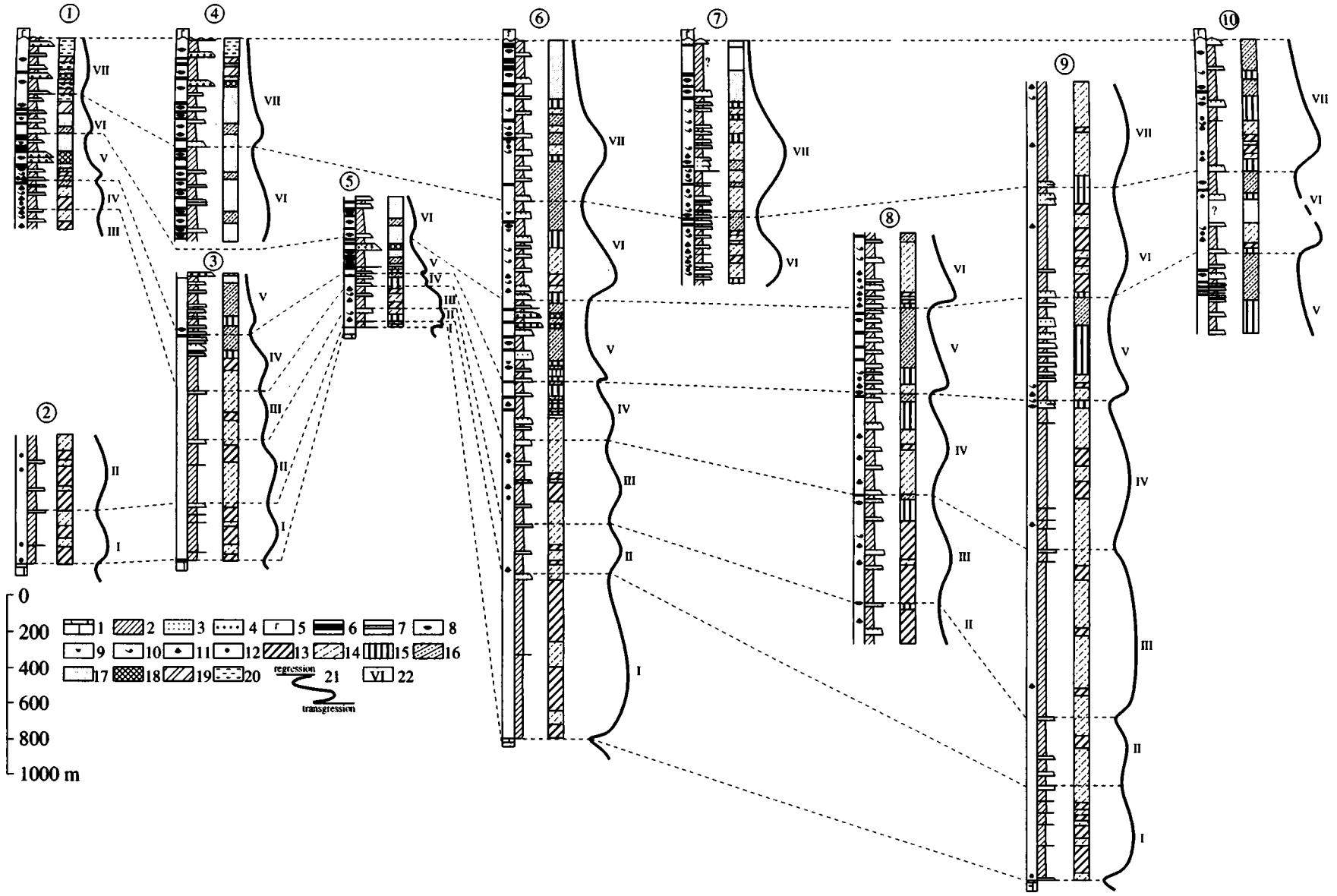

Fig. 2. Correlation of Upper Paleozoic terrigenous sections in the Taimyr Peninsula: (1) limestone; (2) mudstone and siltstone; (3) sandstone; (4) gritstone and conglomerate; (5) tuff and basalt; (6) minable coal seams; (7) thin coal seams; (8) plant remains; (9) non-marine bivalves; (10) marine bivalves; (11) brachiopods; (12) foraminifers; sedimentation settings: (13) deep- and (14) shallow-water sediments of open shelf; (15) deposits of bar belt; (16) sediments of intertidal and supratidal zone (tidal flats and marshes); (17) sediments of lagoon with swamped coasts; (18) deltaic deposits; (19) rocks of relict lagoon/large lake; (20) sediments of lacustrine-alluvial plain; (21) curve of sea-level fluctuation; (22) magnacycle numbers (section numbers correspond to those in Fig. 1).

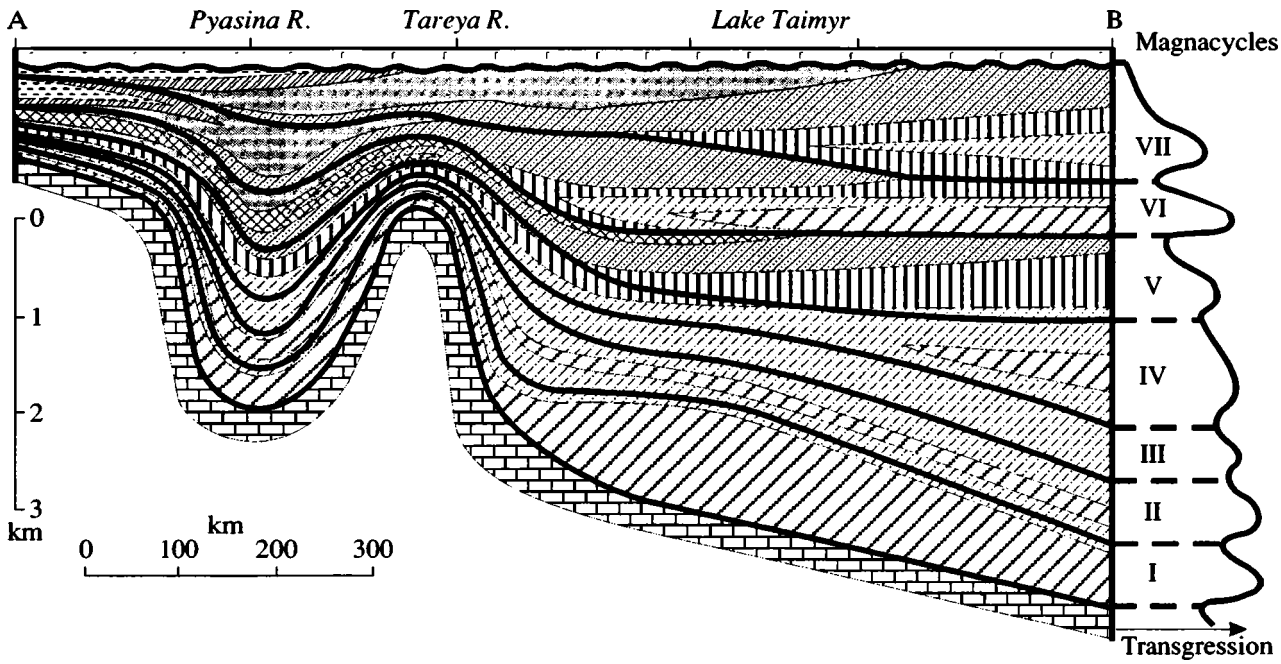

Fig. 3. The W-E-trending lithological–facies profile of Upper Paleozoic deposits in the Taimyr Peninsula (symbols as in Fig. 2).

alternating turbidity siltstone beds, and single non-persistent coal seams (in places of the minable thickness). Large mineralized fragments and casts of trunks, abundant coalified plant detritus, rare identifiable leaf flora, and single Fe-carbonate concretions are common.

(7) *Sandy–silty slightly carbonaceous deposits of relict lagoons (large lakes)*: this is complex of indistinctly alternating, greenish gray turbidity siltstone (dominate) with members of inequigranular sandstone (with lenticular accumulations of gravel and pebble) and rare coal seams (0.1–0.3 m). Fe-carbonate concretions, a slight spotted sideritization of the rocks, and rare coalified plant remains (rhizocretions buried in situ included) are common.

(8) *Variegated conglomerate–sandstone–mudstone sequence of lacustrine-alluvial plain*: variegated red–green mudstone, indistinctly alternating, greenish gray turbidity siltstone, and thick (up to 25 m) members of inequigranular poorly graded sandstone with interlayers of gritstone and conglomerates. The rocks contain Ca- and Fe-carbonate concretions with a high (more than 3%) content of $MnCO_3$, individual imprints of leaf flora, and small rhizocretions buried in situ.

As evident from the W-E-trending lithological profile (Fig. 3), the rock associations mentioned above form a series of diachronous geological bodies, the spatial position of which reflects the history of sedimentation in the paleobasin. The analysis of vertical successions of lithological complexes resulted in establishing the repeated transgression–regression phases of the basin depth changes, which are regarded as magnacycles (Figs. 2, 3). Their beginning corresponds to transition from the regime of a low sea-level stand to its slow rise (the beginning of transgression).

REGIONAL CYCLOSTRATIGRAPHIC UNITS

The entire terrigenous sequence is divided into seven magnacycles. They are identified in all the studied sections according to stratigraphic position, paleontological remains, and peculiar lithological and facies changes. These subdivisions are used as a basis for correlation illustrated in Fig. 2. The revealed correlation potential of the magnacycles indicates that they are natural regional cyclostratigraphic units reflecting stages of the paleobasin evolution.

The first magnacycle is represented in the region by deposits of the open shelf. Its lower boundary is established at the level of cessation of carbonate sedimentation that gave place to accumulation of first terrigenous sediments. This event was caused primarily by deepening of sedimentation basin. As a result, clayey limestones of shallow-water and intertidal zones (the stage of low sea-level), which crown the Lower Carboniferous carbonate sequence within the interval of first several meters, became overlain by mudstone and clayey siltstone of deep-water (stagnation) zones of an outer shelf. Evidently, a sharp sea-level rise could not be a locally event, and boundary between carbonate and terrigenous deposits is close to isochronous. The regressive branch of the cycle (the phase of relatively decreasing paleobasin depth) is recorded by accumulation of lenticular–banded siltstone with rare thin (1–5 m) accumulations of shell detritus and pebbles of clayey–silty rocks (tempestites), and with interlayers (less than 1 m thick) of calcareous silty sandstone (sediments of shallow-water open shelf deposited under wave action). Members (from 1 to 5 m thick) of calcareous silty sandstone appear for the first time at the top of the cycle. The magnacycle is 350–650 m thick in average; its thick-

Table 2. Distribution of paleontological remains in sections of the first, second, and third magnacycles

Sea-level fluctuation curve (Trans-gression ↑)	Magnacycle numbers	III	II	I
Foraminifers	*Archaediscus* ex gr. *angulatus* Sossip.			②
	Neoarchaediscus incertus (Grozd. et Leb.)			②②
	Neoarchaediscus stilus (Grozd. et Leb.)			②②
	Planoarchaediscus stilus Grosd. et Leb.			②⑨
	Planospirodiscus minimus (Grozd. et Leb.)			⑨
	Eostaffella ex gr. *varvarinsis* Brazhn.			②
	Endothyra pzheviса Reitl.		②	
	Eostaffella pseudostruvei (Raus. et Bel.)		②②	
	Globivalvulina minima Reitl.		②②	
	Glovivalvulina ex. gr. *parva* Tscherm.		②②	
	Globivalvulina mosquensis Reitl.		②②	
	Tolypammina glomospiroides Bog. et Juf.	⑨		
	Tolypammina confusa (Gall. et Harl.)	⑨⑨		
	Glomospira gordialis (Jones et Park.)	⑨⑨		
	Orthovertella vercholjanica Sossip.	⑨⑨		
Brachiopods	*Praehorridonia dorsoplicata* Ust.		②②	
	Lanipustula baicalensis (Masl.)	⑨	⑤	
	Jakutoproductus olshaensis Ganel.		⑨⑨	
	Jakutoproductus taimyrensis Ust.		⑨	
	Ovatia ex gr. *ovata* (Hall)			②
	Balkhaschiconcha infima (Ganel.)			②
	Balkhaschiconcha balkhaschensis (Nas.)			⑤
	Inflatia inflata (McChesn.)			②
	Waagenoconcha aff. *irginae* Stusk.	⑤⑤		
	Waagenoconcha wimani Fred.		②	
	Linoproductus prattenianus (Norw. et Pratt.)			②
	Cancrinella alazeica Zav.		⑨	
	Cancrinella cancriniformis (Tschem.)	①		
	Strophalosia delicata Ust.	①⑤		
	Rhynochopora variabilis (Stuck.)	①⑤⑤		
	Levicamera pentameroides (Tschem.)	①		
	Orulgania lukulaensis (Kasch.)		②⑨⑨	
	Tangshanella taimyrica Ust.		②	
	Balakhonia insinuata (Girty.)		⑨⑨	
	Taimyrella pseudodarwini (Einor)		⑨	
	Neospirifer tareiaensis Einor			⑤
Bivalves	*Vacunella* cf. *similis* (Lutk. et Lob.)	①		
	Antraconauta convexa Lutk.	①		

Note: Here, like in Tables 3 and 4, encircled numerals denote amount of sections, from which the species is known; section numbers correspond to those in Fig. 1.

ness is 50 m in the Tareya River basin (Fig. 2, column 5) and as great as 1050 m in the Lake Taimyr area (Fig. 2, column 6).

The rocks contain smaller foraminifer and brachiopod remains (Table 2). Ammonites *Stenopronorites uralensis* (Karp.) and *Syngastrioceras orientale* (Jin.) were found in the lower part of the cycle (Ustritskii and Chernyak, 1963). Ustritskii attributed the found fauna to the lower Bashkirian Substage and distinguished some forms typical of the Early Carboniferous (Ustritskii and Chernyak, 1963; Gramberg *et al.*, 1978). Ganelin described similar forms from the Magar Superhorizon of the Omolon massif, and correlated that superhorizon with the joint range of the late Visean, Serpukhovian, and early Bashkirian (Ganelin, 1977). In the lectostratotype established in lower courses of the Efremov River, stratigraphic range of the cycle corresponds to the upper terrigenous part of the lower Makarov Subhorizon (Ivanov, 1960; Ustritskii and Chernyak, 1963).

The second magnacycle. Sandy–silty deposits of a shallow-water (mobile) open-shelf zone dominate in its lower part. In contrast to the top of the first magnacycle, thickness and amount of sandy interlayers considerably decrease here due to beginning of a new transgression phase. The middle part (the stage of high sea-level) is composed of mudstone and siltstone of the deep-water (below the wave base) shelf zone. Sandy–silty deposits of the shallow-water open-shelf zone become widespread again in the upper regressive part of the cycle. The magnacycle is 350–450 m thick in general, and its thickness decreases to 100 m in the Tareya River basin (Fig. 2, column 5).

The rocks bear foraminifer and brachiopod remains. Ustritskii referred their faunal assemblages (Table 2) to the uppermost Bashkirian and Moscovian Stage of the Middle Carboniferous (Gramberg *et al.*, 1978). Ganelin (1977) correlated these fossils with fauna of the Ol'cha Superhorizon (an upper part of the Bashkirian–Moscovian interval) of the Omolon massif. The second magnacycle corresponds to the upper Makarov Subhorizon in the lectostratotype at the Efremov River (Ustritskii and Chernyak, 1963; Gramberg *et al.*, 1978).

The third magnacycle is similar to the previous one in its structure and lithology. However, members of silty and fine-grained sandstones are thicker here (up to 10 m), the occurrence rate of coquina tempestites is somewhat higher, and proportion of coarse-grained rock varieties is greater among alternating lenticular-banded siltstone beds. These peculiarities are likely related to a general decrease of the paleobasin depth and to the more intense wave action in a shallow-water open-shelf zone. Judging from characteristic features described by Ustritskii and Chernyak (1963), an upper part of the cycle exposed in the Severnaya River section (Fig. 2, column 8) is represented by deposits typical of the intertidal zone (regression maximum). The cycle thickness increases eastward from 200 to 600 m, being at the maximum (1100 m) in upper courses of the Chernokhrebetnaya River (Fig. 2, column 9).

The rocks yield foraminifers, brachiopods, and marine bivalves (Table 2). Ustritskii referred these forms to the Late Carboniferous (Ustritskii and Chernyak, 1963; Gramberg *et al.*, 1978). In opinion of Ganelin, Pronina, and Byakov, the mentioned fossils are characteristic of the Paren' Superhorizon of the Omolon massif, which roughly corresponds to the Upper Carboniferous (Ganelin, 1977). By position in the section and age of fossils, the third magnacycle should be correlated with the lower Turuza Subhorizon (its stratotype is not established). On the other hand, studying exposures at the Severnaya River (lectostratotype of the Byrranga Horizon), Ustritskii and Chernyak (1963) interpreted the section part corresponding to the third magnacycle (Fig. 2, column 8) as spanning the lower part (Gar'kushin and Rudnaya subformations) of the Early Permian Byrranga Formation. They based their conclusion on found shells of *Jakùtoproductus verchoyanicus* (Ustritskii and Chernyak, 1963), the first appearance level of which has been regarded as marking boundary between the Carboniferous and Permian systems (Ustritskii, 1984). Paleontological identifications of the 1960s certainly need verification, because new *Jakutoproductus* species, which are established in the last decade, resemble *Jakutoproductus verchoyanicus* and occur in Carboniferous deposits (Ganelin, 1991). If the third magnacycle is properly identified, the Turuza Horizon should be excluded from the regional stratigraphic scheme, and the age of the Byrranga Horizon must be reconsidered. The problem can be solved ultimately only after reexamination of the Severnaya River section.

The fourth magnacycle. Its lower boundary corresponds in the study region to the level of transition from sandy–silty deposits of the shallow-water shelf to siltstone and mudstone beds deposited in a deep-water setting (the stage of high sea-level stand). Facies characterizing the regressive part of the magnacycle are laterally variable. On the west of the region (Fig. 2, columns 1, 3), deposits of the shallow-water shelf are replaced upwards by sediments of the bar belt (the phase of decreasing paleobasin depth). Top beds of the cycle (the stage of maximal shoaling) are composed of sandstone and siltstone, which accumulated in mud flats and marshes: these rocks are often bioturbated and contain plant detritus, rhizocretions buried in situ, and individual non-persistent coal seams (1–10 cm). Proportion of coastal deposits considerably decreases in the Lake Taimyr area (Fig. 2, columns 6, 8). Further eastward (Fig. 2, column 9), these deposits are replaced by a member (15–20 m thick) of fine- to medium-grained sandstone that contains coalified plant remains (sediments of the bar belt) and overlies the open-shelf deposits. The thickness of magnacycle increases eastward from 450 to 950 m. The lower thickness values of 250 and 100 m are established in the Syradasai and Tareya river basins (Fig. 2, columns 1, 5).

Composition of paleontological remains changes in accord with the vertical and lateral gradation of marine deposits into coastal terrestrial sediments (Table 3). Remains of sea organisms occur everywhere in the lower, larger part of the cycle. Identifiable flora has been encountered only in the upper part of its section, mainly on the west of the region. Identifications by Ganelin, Pronina, and Byakov allowed then to correlate the cycle with the Munugudzhak Horizon of the Omolon massif, which spans the Asselian, Sakmarian, and lower Artinskian interval (Ganelin, 1977, 1994). Judging from the first plausible appearance of the Permian marine fauna, the base of the cycle corresponds to the boundary between the Carboniferous and Permian systems. Verbitskaya who studied a floral assemblage from the upper part of the Byrranga Horizon (Ustritskii, 1984) believed that its taxa are characteristic of the lower part of the Ishanov Horizon in the Kuznetsk basin (Kuzbas) and of the middle part of the lower Burgukli Subhorizon of the Siberian platform. They are attributed to the lower Artinskian Substage (*Verkhnii paleozoi...*, 1988). It is likely that the fourth magnacycle should be correlated with the lower part of the Byrranga Horizon based on its position in the section and age. On the other hand, Ustritskii and Chernyak (1963) referred this part of the section exposed along the Severnaya River (Fig. 2, column 8) to uppermost Byrranga and lowermost (about 50 m) Sokolinyi beds.

The fifth magnacycle is of a clear asymmetrical structure detectable in the region. The transgressive part of the magnacycle is reduced and represented in most sections by a thin (10–50 m) member of sediments characteristic of shallow-water open shelf and bars. Deep-water shelf deposits appear only in the east of the region (Fig. 2, column 9). The regressive part, topmost beds of which recorded the early Permian maximal drop of sea level, is more typical of the study region, and its lithological composition considerably varies in lateral direction. In the western Taimyr, the sea-level drop resulted in appearance of deltas (thick members of inequigranular sandstone with interlayers of gritstone and conglomerate, which rest with hiatus on underlying deposits) and lagoons, coasts of which were swamped. A direct consequence of this event is the first appearance of coal seams having a minable thickness (more than 0.7 m). In the Syradasai River basin (Fig. 2, column 1), the regressive part of the magnacycle contains 8 to 15 minable seams, the total thickness of which is up to 40 m. The coal productivity of the cycle declines to the northeast, where lagoonal sediments are replaced by low-carbonaceous deposits of mud flats and marshes (Fig. 2, columns 3, 5). In the Tareya River basin, the magnacycle encloses only six minable seams less than 9 m thick in total. In eastern Taimyr Peninsula, proportion of rocks representing the sandy–conglomerate deltaic complex markedly decreases, and productive coal-bearing lagoonal deposits are missing. Near the Lake Taimyr (Fig. 2, columns 6, 8), this complex is replaced by intertidal and supratidal deposits comprising only rare coal seams (0.1–0.4 m). Further eastward, coal-free rocks of the bar belt dominate in the regression part of the cycle (Fig. 2, columns 9, 10), whereas low-carbonaceous deposits of mud flats and marshes occur only at the top (the regression maximum) of the magnacycle. The magnacycle thickness varies from 200–300 m in the Syradasai and Tareya river basins to 700 m in upper courses of the Chernokhrebetnaya River and thus increases eastward.

Rare identifiable remains of sea organisms have been encountered in the smaller lower (transgressive) part of the cycle (Table 3). Ganelin considered these remains as typical of the Dzhigdali Horizon of the Omolon massif, which he correlated with the upper Artinskian, entire Kungurian, and lower Ufimian (Ganelin, 1984; Ganelin *et al.*, 1990). In the larger upper (regressive) part of the cycle, terrestrial plant remains are widespread, though their abundance substantially decreases eastward. According to Verbitskaya, these remains (Table 3) are typical of flora known from upper parts of the Ishanov, Kemerovo, and Usyatsk horizons of the Kuznetsk basin or from the Burgukli Horizon of the Siberian platform, its lower beds excluded. The cycle is correlated with the upper Artinskian–Kungurian interval (*Verkhnii paleozoi...*, 1988). Judging from paleontological characteristic and position in the section, the fifth magnacycle likely corresponds to the upper part of the Byrranga Horizon and whole Sokolinyi Horizon (stratotype not established). Ustritskii and Chernyak (1963) attributed rocks of the magnacycle to the upper larger part of the Sokolinaya Formation of the Byrranga Horizon stratotype (Severnaya River).

The sixth magnacycle is remarkable owing to considerable lateral changes in lithology and facies, which imply a great paleogeographic contrast of sedimentation settings. The transgressive part of the cycle corresponds in its terminal portion to the Late Permian maximum of the paleobasin deepening. Within the eastern Taimyr (Fig. 2, columns 6–10), it is composed of sediments of an open shelf (from silty–sandy sediments of relatively shallow-water origin to deep-water mudstone–siltstone). The sediments grade via transition zone of 10–15 m thick into low-carbonaceous supratidal deposits (top of the fifth magnacycle). The impact of sea transgression is less obvious in the western Taimyr (Fig. 2, columns 1, 4, 5). It is evident from an upward decreasing thickness of coal seams and from appearance of a low-carbonaceous member (20–80 m) deposited in a tidal flat. The sea-level drop resulted in shallowing of open-shelf sedimentation settings of the eastern Taimyr and intensified effect of wave and tidal processes (lenticular–banded alternation of siltstone beds often bioturbated, displaying abundant fucoids). The regression maximum is recorded by appearance of slightly carbonaceous intertidal and supratidal deposits at the top of the cycle (Fig. 2, columns 6–10). The regressive part of the cycle is composed of coal-bearing rocks of lagoonal genesis in the western Taimyr, Tareya River basin, and lower courses of the Pyasina River (Fig. 2, columns 3, 5). In the Yenisei River area, con-

Table 3. Distribution of paleontological remains in sections of the fourth and fifth magnacycles

IV	V	Transgression	Sea-level fluctuation curve / Magnacycle numbers	
①			*Hyperammina* aff. *bulbosa* Cush. et Wat.	Foraminifers
①	⑧		*Reophax gerkei* Vor.	
①			*Tolypammina glomosporoides* Bog. et Juf.	
①①	①		*Tolypammina confusa* (Gall. et Harl.)	
①			*Orthovertella verchojanica* Sossip.	
①			*Orthovertella* ex. gr. *protea* Crespin	
	①		*Hemigordius* ex. gr. *schlumbergeri* (How.)	
①			*Jakutoproductus cheraskovi* Kasch.	Brachiopods
①			*Jakutoproductus expositus* Ganel.	
①			*Jakutoproductus rugosus* Ganel.	
①			*Uraloproductus* cf. *stuckenbergianus* Krot.	
①			*Achunoproductus* cf. *achunovensis* (Step.)	
①			*Waagenoconcha wimani* Fred.	
① ①			*Cancrinella alazeica* Zav.	
①			*Anidanthus bojkovi* Step.	
①			*Anidanthus* cf. *aagardi* (Toula)	
⑥			*Anidanthus* cf. *dicksoni* (Einor)	
	①①①		*Rhynchopora variabilis* (Stuck.)	
①			*Spiriferella* cf. *burgaliensis* (Zav.)	
	⑧		*Tomiopsis taimyrensis* Tschern.	
①①①			*Yakovlevia mammatiformis* (Fred.)	
①			*Vacunella* cf. *similis* (Lutk. et Lob.)	Bivalves
	①		*Taimyrensis taimyrensis* Lutk.	
①			*Taimyria* cf. *longa* Lutk.	
	⑥		*Streblopteria engelhardi* (Eth. et Dun.)	
	⑥		*Streblopteria* ex gr. *pusila* (Schloth.)	
① ①			*Praeundulomia* aff. *petscherica* Mur.	
	⑥		*Antraconauta diagonalis* Chalf.	
	⑥		*Antraconauta sendesoni* Chalf.	
		①	*Abiella* (?) *piluta* (Loh.)	
		①	*Naiadites* (?) *rombifera* (Lut.)	
		①	*Mrassiella* (?) cf. *orbiculata* (Lut. et Lob.)	
		①	*Mrassiella* (?) et. *Insulta* (Lut. et Lob.)	
	① ⑥		*Spenophyllum subrotundatum* Neub.	Flora
①		① ⑥	*Koretrophyllites gracilis* Verb.	
	① ① ⑥ ①		*Koretrophyllites setosus* Radcz.	
⑥ ⑥	① ⑥ ① ⑤ ① ⑥ ⑤ ①		*Paracalamites vicinalis* Radcz.	
	① ⑥ ① ⑥ ①		*Paracalamites costatus* Gorel.	
	① ① ①		*Prynadaeopteris maneichensis* (Zal.) Radcz.	
	① ① ⑥ ①		*Pecopteris immanis* Schv.	
	① ① ⑥ ①		*Zamiopteris longifolia* Schv.	
		①	*Zamiopteris stanovii* Radcz.	
⑥	① ① ⑥ ①		*Glottopyllum usjatense* Gorel.	
① ⑥	① ⑤ ⑥ ① ⑥		*Cordaites singularis* (Neub.) S. Meyen	
⑥	① ⑥ ⑤ ① ⑥ ① ⑤ ⑥		*Cordaites latifolius* (Schv.) S. Meyen	
		⑤	*Cordaites candalepensis* (Zal.) S. Meyen	
⑥	① ⑤ ① ⑥ ① ⑤ ⑥		*Rufloria tebenjkovii* (Schv.) S. Meyen	
⑥⑥①⑧	⑤⑥ ① ⑥ ① ⑥ ⑧		*Rufloria maibyrica* (Schv.) S. Meyen	
①⑥①⑧	⑤ ① ⑥ ① ⑥ ⑥ ⑤		*Rufloria derzavinii* (Neub.) S. Meyen	
⑥	⑤ ① ⑥ ①		*Evenkiella zamiopteroidea* Radcz.	
①⑥①	⑤ ① ⑥ ① ⑧ ⑥		*Crassinervia tunguskana* Schv.	
⑥	① ⑥ ①		*Crassinervia oblongifolia* Radcz.	
⑥	① ①		*Lepeophyllum acutifolium* Radcz.	
	① ⑥ ①		*Samaropsis subpatula* Such.	
	⑤ ① ① ⑥ ⑤		*Samaropsis skokii* Neub.	
	⑥ ⑤		*Samaropsis khalfinii* Such.	
⑥	① ⑥ ⑤ ⑥		*Cordaicarpus ellipticus* Radcz.	
⑥	① ①		*Cordaicarpus nasutus* Such.	
	⑤⑥ ① ①		*Bardocarpus depressus* (Schm.) Neub.	

nections of sedimentation settings with the sea basin ceased due to the shoreline retreat, and slightly carbonaceous sandy–silty deposits of large lakes, the relict lagoons, constitute the upper part of the cycle (Fig. 2, column 1). Variegated conglomerate–sand–muddy sequence that accumulated in a coastal lacustrine-alluvial plain corresponds here to the regression maximum. Its minable coal seams occur only in the western Taimyr Peninsula. The coal productivity is at the maximum in lower courses of the Pyasina River, where 12 to 16 minable seams having total thickness of 35 m are known. The coal potential gradually decreases westward and eastward of the "Pyasina maximum." In the Yenisei River area, the cycle encloses 1 to 5 minable seams from 0.8 to 3.1 m in total thickness. Six minable coal seams 14.2 m thick in total were revealed in the Tareya River basin. In eastern Taimyr Peninsula, the cycle is lacking minable coal. The magnacycle thickness is 550–750 m in average, being decreased to 250 m in the Syradasai and Tareya river basins (Fig. 2, columns 1, 5).

In compliance with lateral facies changes, the cycle contains mainly marine fauna on the east and terrestrial flora on the west (Table 4). According to Ustritskii (1984), its faunal assemblage indicates that this part of the whole sequence corresponds to Ufimian deposits of the Russian platform. Solomina and Preobrazhenskaya (1993) correlated this interval with the uppermost Ufimian and lower Kazanian. Ganelin attributed the lower part of the magnacycle to the uppermost Kungurian. His dating is based on abundant *Megousia kuliki* (Fred.), which were found in samples collected in the Lake Taimyr northwestern coast. He also believes that fossils found in exposures along the Belosnezhka River (Solomina and Preobrazhenskaya, 1993) are characteristic of upper (Kazanian) beds of the Omolon Horizon. Ganelin (1994) explained such an abrupt change in paleontological assemblages by a stratigraphic hiatus between them. According to my observations in the Lake Taimyr area, this part of the magnacycle composed of deep shelf sediments is lacking either washout or break in sedimentation, though I do not exclude presence of condensed sediments. In the western Taimyr Peninsula, where the same interval is composed of intertidal to terrestrial deposits, neither lithological nor paleobotanical data suggest presence of a regional hiatus (Shishlov and Verbitskaya, 1990). Verbitskaya correlated the assemblage of plant remains occurring in the cycle with flora of the Starokuznetsk, Mitin, Kazankov–Markov, and Uskat horizons of the Kuznetsk basin and with that of the Pelyatka Horizon of the Siberian platform. The listed stratigraphic units are correlated with the Ufimian–Kazanian interval (*Verkhnii paleozoi...*, 1988). Hence, according to paleontological data, the base of the sixth magnacycle (the beginning of the transgression) nearly coincides with the Lower–Upper Permian boundary. The Kungurian species *Megousia kuliki* from the lower part of the cycle is likely of a wider stratigraphic range. In the northern part of the Russian platform, it is known from the Kachgort and Ekusha formations, which are equivalents, according to the regional stratigraphic scheme of 1990, of the Ufimian Solikamsk and Sheshma horizons. An imprecise identification of these remains seems to be possible as well. In exposures along the Tsvetochnaya River, Ustritskii (1963) identified at the same level a similar species *Megousia yakutica* (Lich.) of a much wider stratigraphic range.

In its stratigraphic range, the sixth magnacycle corresponds to the whole Baikura Horizon coupled with the lower part (about 50 m) of the Chernoyarsk Horizon of the Tsvetochnaya River section representing the Baikura Horizon lectostratotype (Ustritskii and Chernyak, 1963). My correlation suggests that the same interval in exposures of the Belosnezhka Creek was attributed by Solomina and Preobrazhenskaya (1993) to the uppermost Sokolinyi (about 140 m) and Belosnezhka horizons. Their inference is consistent with paleontological data, and the aforementioned sections (Fig. 2, columns 7, 8) are correlative with a complete Permian interval, rocks of which are exposed along the Uglenosnaya River (Fig. 2, column 6).

The seventh magnacycle corresponds to the final depositional stage of Upper Paleozoic terrigenous sediments in the Taimyr Peninsula. During this stage, diverse (from marine to continental) and changeable (in space and with time) environments set up in the paleobasin. On the east (Fig. 2, columns 9, 10), the sea transgression brought into restoration the offshore shelf environments. In the Lake Taimyr area (Fig. 2, columns 6, 7), the same level reveals cyclic alternations of marine, bar, and intertidal deposits. Further westward, in lower reaches of the Pyasina River (Fig. 2, column 4), the transgressive part section of the cycle is composed mainly of lagoonal deposits. A member (20–25 m) that accumulated in a tidal flat is composed here of low-carbonaceous siltstones bed displaying fine clear alternations and corresponds to the stage of high sea-level stand. In areas adjacent to the Yenisei River valley (Fig. 2, column 1), sediments of the coastal lacustrine-alluvial plain give way to deltaic and productive lagoonal deposits bearing coal. On the east (Fig. 2, column 10), the regressive part of the cycle is composed of subtidal and intertidal low-carbonaceous deposits, which are replaced in the Lake Taimyr area (Fig. 2, columns 6, 7) by productive coal-bearing deposits of lagoonal genesis. In response to regression in the western Taimyr Peninsula, first the Yenisei River area (Fig. 2, column 1) and then lower reaches of the Pyasina River (Fig. 2, column 4) were transformed into a coastal lacustrine–alluvial lowland, where the variegated conglomerate–sandy–argillaceous deposits accumulated under subaerial conditions. Changes in time–space localization of lagoons with swamped coasts controlled coal accumulation in the magnacycle. In the Yenisei River area, a single coal seam 0.8–1.7 m thick is confined the lower transgressive part of the magnacycle. The coal productivity is much greater eastward, in the Pyasina River lower courses, where the transgressive cycle part encloses 17 minable coal seams 41 m thick in total

VI	VII	Transgression	Sea-level fluctuation curve / Magnacycle numbers	
			Orthovertella ex gr. *protea* Crespin	Foraminifers
			Frondicularia aff. *planilata* Gerke	
			Frondicularia inflata Cerke	
			Frondicularia mica var. religia Gerke	
			Frondicularia amygdalaeformis Gerke	
			Frondicularia pseudotriangularis Gerke	
			Nodosaria incelebrata Gerke	
			Nodosaria noinskii Tcherd.	
			Nodosaria krotovi Tscherd.	
			Nodosaria solidissima Gerke	
			Nodosaria cuspidatula Gerke	
			Nodosaria pseudoconcinna M.-Macl.	
			Pseudonodosaria ventrosa Schleif.	
			Protonodosaria proceraformis Gerke	
			Glomospira ex gr. *gordialis* Parker et Jones	
			Ammodiscus ex. gr. *semiconstrictus* Wat.	
			Rectoglandulina pygmeaformis M.-Macl.	
			Rectoglandulina borealis Gerke	
			Striapustula koninckiana (Keys.)	Brachiopods
			Cancrintlloides yuregensis Sol.	
			Cancrinelloides obrutschewi (Lich.)	
			Magadania bajkurica (Ustr.)	
			Megousia cf. *kuliki* (Fred.)	
			Megousia jakutica (Lich.)	
			Strophalosia cf. *tolli* (Fred.)	
			Strophalosia bajkurica Ustr.	
			Rhynchopora lobjaensis Tolm.	
			Spiriferella lita Fred.	
			Brachythyrina sibirica Tscherm.	
			Bajkuria cf. *dorsosinuata* Ustr.	
			Tomiopsis taimyrensis Tschern.	
			Olgerdia zavodowskyi Grig.	
			Terrakea cf. *belokhini* Gan.	
			Streblopteria levis (Lutk. et Lob.)	Bivalves
			Streblopteria engelhardi (Eth. et Dun.)	
			Myonia longa (Lutk. et Lob.)	
			Myonia komiensis (Maslen.)	
			Kolymia cf. *inoceramiformis* Lich.	
			Kolymia cf. *irregularis* Lich.	
			Sanguinolites bicarinatus Keus.	
			Martjanowskia baidajevae Radcz.	
			Koretrophyllites polcaschtensis (Cachl.) Radcz.	Flora
			Annularia batschatensis Rascz.	
			Phyllotheca ninaeana Radcz.	
			Paracalamites robustus Zal.	
			Prynadaeopteris anthrisifolia (Goepp.) Radcz.	
			Pecopteris leninskiensis (Chachl.) Radcz.	
			Pecopteris taimyrensis Schv.	
			Callipteris pseudoaltaica Radcz.	
			Glottopyllum primaevum Radcz.	
			Cordaites mediocris (Gorel.) S. Meyen	
			Cordaites insignis (Radcz.) S. Meyen	
			Cordaites clerci Zal.	
			Cordaites candalepensis (Zal.) S. Meyen	
			Rufloria synensis (Neub.) S. Meyen	
			Crassinervia minima Such.	
			Samaropsis irregularis Neub.	
			Tungussocarpus elongatus Such.	

Table 4. Distribution of paleontological remains in sections of the sixth and seventh magnacycles

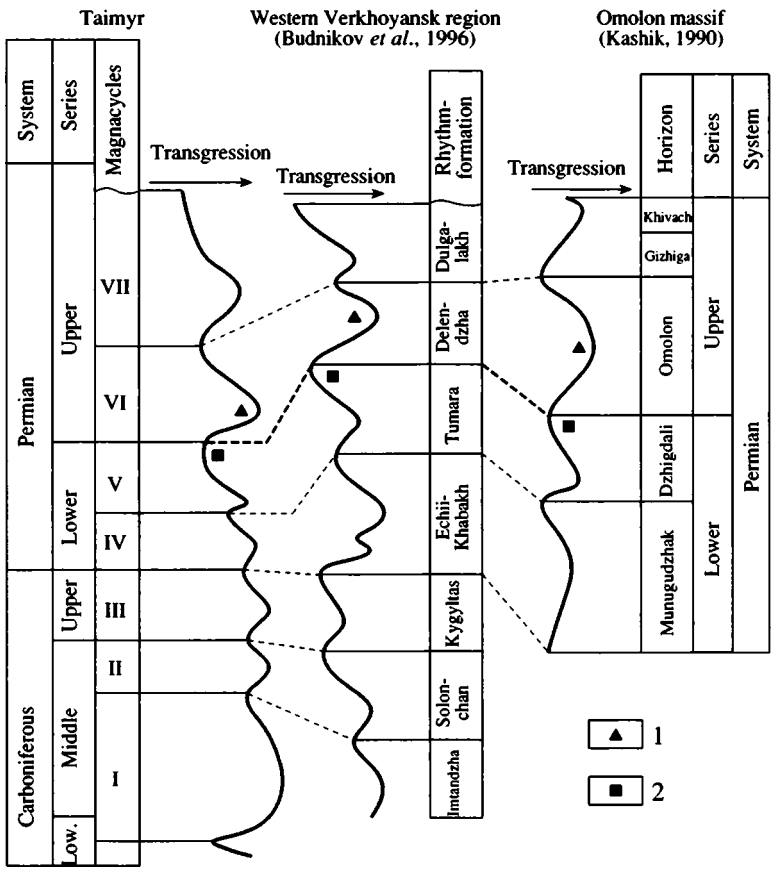

Fig. 4. Curves illustrating Late Paleozoic sea-level fluctuation in the Taimyr, Omolon, and Verkhoyansk sedimentation basins: (1) Late Permian transgression maximum, (2) Early Permian regression maximum.

(upward in the sequence, coal seams become thinner and less frequent). In the eastern Taimyr Peninsula, the regressive part of the cycle represents the only coal-productive horizon of the entire Upper Paleozoic terrigenous sequence. From 14 to 17 minable coal seams 30.9 m thick in total are known at that level in areas adjacent to western coast of the Lake Taimyr. Further eastward, the coal potential decreases and east of Lake Taimyr the magnacycle contains only individual coal sheds. The upper boundary of the magnacycle is at the level separating terrigenous and volcanogenic sediments. First tuffs and lava flows overlie with stratigraphic unconformity the dissected and variably eroded surface of the seventh magnacycle. This uneven surface with undulation amplitudes of 5 to 15 m high and 50 to 200 m long is observable in exposures throughout the study region (Syradasai River basin, Pyasina River lower courses, Ledyanaya Bay area, etc.). It originated in the course of shallow and non-uniform erosion before lava eruptions. The magnacycle varies in thickness from 350 m on the southwest to 1350 m on the northeast of the region.

Marine fauna is found only in the transgressive part of the cycle and only within the eastern Taimyr Peninsula (Table 4). G.P. Sosipatrova compared the foraminifer assemblage of the cycle with that of the Kozhevnikov Formation of the Kazanian Stage (Solomina and Preobrazhenskaya, 1993). According to M.M. Astaf'eva who studied bivalves, deposits enclosing them can be correlated with the Khal'pirki Horizon of the Verkhoyansk region and with the Khivach Horizon of the Kolyma–Omolon region, which are arbitrarily attributed to the upper Kazanian (Solomina and Preobrazhenskaya, 1993). Abundance of marine fauna markedly decreases northwest of the Lake Taimyr (Chernoyarsk River basin), and it is unknown in the western Taimyr Peninsula, where terrestrial flora is widespread (Table 4). Verbitskaya (Shishlov and Verbitskaya, 1990) correlated this flora with plant remains of the Leninsk, Gramoteino, and Tailugan horizons of the Kuznetsk basin or with floras of the Degali and Gagarii horizons of the Siberian platform (*Verkhnii paleozoi...*, 1988). M.V. Durante believes that plant remains from the cycle are characteristic of the interval from the upper Il'inskaya to lower Erunakovo subgroups of the Kuznetsk basin (upper Kazanian–Tatarian). In her opinion, the top of terrigenous sequence in the Taimyr Peninsula is stratigraphically lower than the top of the Tailugan Formation in the Kuznetsk basin and, hence, a bit lower than the Permian–Triassic boundary (Solomina and Durante, 1991).

Table 5. Correlation scheme of regional biostratigraphic (horizons) and cyclostratigraphic (magnacycles) units distinguishable in the Upper Paleozoic terrigenous sequence of the Taimyr Peninsula

System	Series	Stage	Horizons		Magnacycles
Permian	Upper	Tatarian	**Chernoyarsk** (in the stratotype along Vysokaya River; Solomina and Durante, 1991)		VII
		Kazanian	**Baikura** (in the stratotype along Tsvetochnaya River; Ustritskii and Chernyak, 1963)		VI
		Ufimian			
	Lower	Kungurian	**Sokolinyi** (no stratotype)		V
		Artinskian	**Byrranga** (in the stratotype along Severnaya River; Ustritskii and Chernyak, 1963)		IV
		Sakmarian			
		Asselian			
Carboniferous	Upper	Gzhelian			III
		Kasimovian			
	Middle	Moscovian	**Makarov** (in the stratotype along Efremov River; Ustritskii and Chernyak, 1963)	Upper subhorizon	II
		Bashkirian		Lower subhorizon	I
	Lower				

In its stratigraphic range, the seventh magnacycle corresponds to the Chernoyarsk Horizon in the lectostratotype established by Solomina and Durante (1991) at the Vysokaya River (a tributary of Chernye Yary River), but Solomina and Preobrazhenskaya (1993) attributed the lower part of the magnacycle to the Tsvetochnyi Horizon. This inconsistency is associated with diverse identifications of the Chernoyarsk Horizon base. In the eastern Taimyr, that base is traditionally placed at the top of last interlayer with marine fauna (Ustritskii and Chernyak, 1963). This criterion is not universal because of considerable vertical and lateral facies changes characteristic of the lower part of the seventh magnacycle in the Lake Taimyr area. As a result, burials of marine fauna alternate here with beds bearing terrestrial flora remains. As a consequence, the cycle intervals with coal seams and abundant plant remains are attributed to the Chernoyarsk Horizon. The concurrent deposits with marine fauna were originally placed into the upper part of the Baikura Horizon (Ustritskii and Chernyak, 1963), while later on they were distinguished as a separate Tsvetochnyi Horizon (Ustritskii, 1984). As a result, the stratigraphic range of the lower Chernoyarsk Subhorizon in the Vysokaya River lectostratotype (Solomina and Durante, 1991) turned out to be coincident with that of the Tsvetochnyi Horizon in the Belosnezhka Creek key section (Solomina and Preobrazhenskaya, 1993).

CONCLUSIONS

Regional biostratigraphic units of the Upper Paleozoic known in the Taimyr Peninsula are inappropriate for reliable and detailed correlation of remote sections that is desirable. This is a consequence of lateral changes in paleontological assemblages, which are controlled by facies variability of deposits. Combined sedimentological and cyclostratigraphic methods enhance the correlation reliability. Cycles of the fifth order (magnacycles) established using these methods correspond to major transgression–regression stages in evolution of the paleobasin. Yielding specific fossil assemblages, these cycles differ from each other in composition and structure and are identifiable throughout the study region. Their boundaries appear to be isochronous, at least at the resolution level of paleontological methods. The correlative curves depicting sea-level fluctuations in the Taimyr, Verkhoyansk (Budnikov *et al.*, 1996), and Kolyma–Omolon (Kashik, 1990) paleobasins are appropriate as a basis for the interregional correlation (Fig. 4) The regression maximum at the end of the Early Permian and the transgression maximum of the Late Permian are especially distinct in these curves. Accordingly, we may suggest that magnacycles are interrelated with eustatic sea-level fluctuations. Provided an additional biostratigraphic substantiation, the magnacycles can be used for elaborating a new regional stratigraphic scheme for the Upper Paleozoic of the Taimyr Peninsula.

It is clear that principle of distinguishing magnacycles (reconstruction of changes in the paleobasin depth

based on the analysis of successions of lithological–facies complexes) differs fundamentally from the procedure of distinguishing horizons based on biostratigraphic criteria (sequence intervals with their characteristic fossil assemblages). Therefore, boundaries and ranges of bio- and cyclostratigraphic units can be not coinciding (Table 5). Moreover, correlations based on cyclostratigraphic criteria may differ in some cases from those based on biostratigraphic data. Stratigraphic ranges of the Baikura and Belosnezhka horizons coincide as is shown above, whereas the Tsvetochnyi Horizon corresponds to the lower Chernoyarsk Subhorizon. Everywhere in the region, the third magnacycle and the lower part of the fourth magnacycle yield fossils characteristic of the Turuza Horizon and correspond to the Byrranga Horizon stratotype. In this connection, the Turuza, Belosnezhka, and Tsvetochnyi horizons are missing from Table 5 illustrating the relation between cyclostratigraphic units and regional horizons in stratotypes. It is likely that contradictions and inconsistencies mentioned above show that none of methods is able to produce indisputable results. Thus we need in a further comprehensive study, the primary goal of which should be the reexamination of stratotype sections of Upper Paleozoic regional horizons known in the Taimyr Peninsula.

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Boreal–Tethyan Mollusk Migrations at the Jurassic–Cretaceous Boundary Time and Biogeographic Ecotone Position in the Northern Hemisphere

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Abstract—Mollusk migrations of various intensity in the Kimmeridgian to Valanginian time span were established in the Boreal Atlantic (West and East European Provinces), Boreal Pacific (Chukotka–Canadian and Boreal Pacific Provinces), and Arctic Realms of the Panboreal Superrealm. According to intensity degree, the migrations are classified as expansions, i.e., mass migrations, and influence migrations, i.e., penetration of separate taxa. Migrations of the cross- and unidirectional types are distinguished according to directions of taxa exchange. Mollusks (ammonites, belemnites, and bivalves) are subdivided into Tethyan and Boreal forms, which inhabited areas south of 45°N, and north of 50°N, respectively. Low-boreal mollusks distinguished among the latter were characteristic of an ecotone between the Panboreal and Tethys–Panthalassa Superrealms, and Boreal-Arctic taxa dwelt north of 60°N. The ecotone of the Boreal Atlantic Realm was situated between 50° and 55°N. The ecotone zone persistently existed in the Boreal Pacific Realm. The ammonite ecotone of the Chukotka–Canadian Province (Primor'e) was between 45° and 55°N. In the Boreal Pacific Province (northern California), an ecotone of the Tithonian–Valanginian time was located between 40° and 50°N. Water temperature lower in the north was the major factor that influenced Boreal–Tethyan migrations and positioning of biogeographic ecotones. The coincidence of transgression peaks with the ammonite migration events is characteristic only of the Kimmeridgian–Middle Volgian time, when northward migrations of the Tethyan ammonites coincided with sea level rises. The Berriasian expansion of berriasellids to the Central Russian Sea was not associated with eustatic events. It might be a consequence of a sea way opening between the North Caucasian and Central Russian seas.

Key words: Jurassic, Cretaceous, Boreal, Tethys, ecotone, biogeography, migrations, mollusks.

INTRODUCTION

Elucidation of dynamics of Boreal–Tethyan mollusk migrations at the Jurassic–Cretaceous boundary time, especially of ammonites and buchiids (bivalves), is extremely important for solution of problems associated with zonal correlation between the Tithonian and Volgian stages, and between the Berriasian and Boreal Berriasian. In the Panboreal Superrealm, the migrations occurred, as is established (Saks *et al.*, 1971), between the Boreal Atlantic (North Western and Eastern Europe to the north of 50°N), Arctic (modern Arctic seas and adjacent lands to the south of the Arctic Circle), and Boreal Pacific (Pacific Ocean and surrounding lands to the north of 45°N) Realms (Fig. 1). Many publications are devoted to the analysis of migrations in the Boreal Atlantic (Mesezhnikov *et al.*, 1971; Rawson, 1981; Kelly, 1983; Michalik, 1995; Vašiček and Michalík, 1999; Baraboshkin, 2001; and others) and Boreal Pacific (Sey and Kalacheva, 1983, 2000; Zakharov and Bogomolov, 1996; Zakharov *et al.*, 1996) Realms. However, area of the biogeographic ecotone between the Panboreal and Tethys–Panthalassa Superrealms did not attract a considerable attention up to now. In the Boreal Pacific Realm (Chukotka–Canadian Province), its geographical position during the Late Triassic, Jurassic, and Early Cretaceous was established based on mollusk distribution in order to evaluate a conceivable meridional displacement of terranes (Zakharov *et al.*, 1996). In the Boreal Atlantic Realm, positioning of the ecotone area in the late Volgian and early Neocomian was elucidated based on ammonites (Zakharov and Bogomolov, 1996, 1998).

Bearing in mind a lack of the GSSP officially accepted for the Jurassic–Cretaceous boundary (Zakharov *et al.*, 1996) and difficulties in correlation between the Boreal and Tethyan successions, we show in correlation schemes only one of possible levels of that boundary. In our view, the problem of relationship between the Volgian and Tithonian stages is still far from an ultimate solution, and we can discuss only a preliminary correlation. We also believe that there is no strict evidence for the age equivalence of the lower Berriasian and upper Volgian substages.

The undeniable correlation of the uppermost Valanginian top in Siberia, Western Europe, and North America is also impossible in view of incomplete

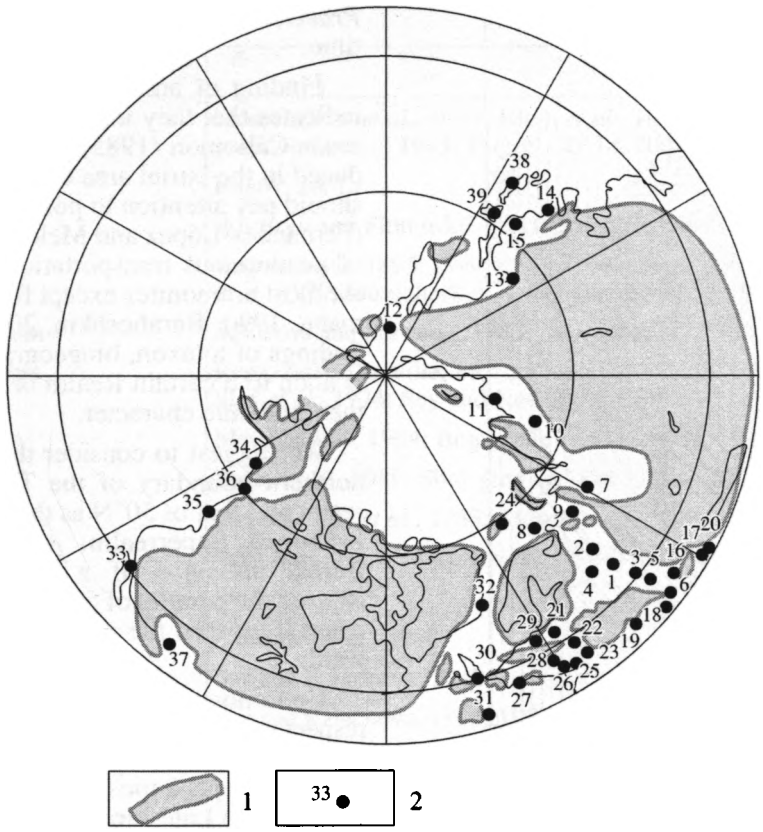

Fig. 1. Major localities of fossils analyzed in this work: (1) land; (2) localities (numbers correspond to those in the table).

records. The position of the *Homolsomites bojarkensis* Zone still remains uncertain. Researchers place it either at the base of the Hauterivian, or in the upper Valanginian (Rawson, 1981; Shul'gina, 1985; Bogomolov, 1989; Marek and Shulgina, 1996). This should be kept in mind when the age is not specified advisedly.

1.1. MATERIALS

We considered data on ammonite, belemnite, and bivalve migrations in the Northern Hemisphere (table, Fig. 2) during the Late Jurassic (Kimmeridgian and Volgian ages) and Early Neocomian (Boreal Berriasian–Valanginian time). Data on migrations within substage time spans were grouped and analyzed. We tried to take into consideration all the data on studied collections and available in the literature. In our work, we encountered traditional difficulties: a common lack of pictures of taxa listed in publications, inaccessibility of collections of fossils presented in low-quality images, and impossibility to identify forms from photographs only.[1] For instance, there are only few images of sub-Mediterranean ammonites encountered in Volgian deposits of the East European Province. We admit that some Tithonian, Berriasian, and Valanginian ammonites from the Far East (Sey and Kalacheva, 1983, 1999) are in the imperfect preservation state. Moreover, there is no way to identify with certainty even the generic affiliation of buchiids and inoceramids from the Tithonian of Cuba (Myczyński, 1999) using their images only. Accordingly, when information is particularly important, we indicate whether or not the corresponding form is pictured, and how precise its identification is. Other things being equal, the preference is given to an illustrated form or to a conclusion based on personal examination of fossils in collections.

In addition to migrations proper, we must take into account the effect of "parallel evolution" implying that the same features appear, sometimes concurrently, in representatives of different groups. Contrary to Olóriz (1990), we do not attach much importance to this factor. Perhaps, the most significant examples of parallel development of similar features in different ammonite groups are the *"Gravesia"* occurrence in Kenya (Verma and Westermann, 1984), an independent development of perisphinctids with virgate branching ribs during the early–middle Volgian in the East and West European Provinces, and bipolar distribution of thin-ribbed perisphinctids *Kossmatia, Virgatosphinctes*, and

[1] Like Bengtson and Kakabadze (1999, p. 227–228), we can mention the major problems of a paleobiogeographic analysis. These are the absence of data on biogeographically important taxa except for their listing, taxonomic uncertainties, contingency of distribution, diverse age interpretations, facies inconsistency, and sampling deficiency.

Fig. 2. Generalized position of molluscan biochores in the Northern Hemisphere at the Jurassic–Cretaceous boundary time (position of continents after Smith and Briden, 1977; simplified land–sea relationship after Saks *et al.*, 1971; Rawson, 1973; Imlay, 1984; Thierry, 2000; nomenclature of biochores after Saks *et al.*, 1971): (1) land; (2) Arctic Realm; (3) East and (4) West European Provinces of the Boreal Atlantic Realm; (5) Chukotka–Canadian and (6) Boreal Pacific Provinces of the Boreal Pacific Realm; (2–6) Panboreal and (7) Tethys–Panthalassa Superrealms.

Praechetaites at the Jurassic–Cretaceous boundary time.

Finding of ammonites in some Realm not always indicates that they inhabited the area or were eudemic sensu Callomon (1985), i.e., occurred and were reproduced in the burial area of their shells.[2] Therefore, one should pay attention to possible burials of empty shells (Fernández-López and Meléndez, 1996). The influence of posthumous transportation was likely insignificant for most ammonites except for Phylloceratida (Westermann, 1990; Baraboshkin, 2001). In the case of single findings of a taxon, biogeographic affiliation of which is alien to a certain Realm or Province, one can doubt their eudemic character.

We suggest to consider the parallel of 45°N as the northern boundary of the Tethys–Panthalassa Superrealm and that of 50°N as the southern boundary of the Panboreal Superrealm. Accordingly, we admit the Boreal influence, if a taxon migrating southward crossed the parallel of 50°N, and the Tethyan influence, when it crossed the parallel of 45°N migrating northward.

Up to now, there is a considerable uncertainty with respect paleocoordinates of most terranes. According to present paleotectonic models par example, the Sikhote-Alin represents a mosaic of many terranes, positions of which in the Late Jurassic is defined within a comparatively wide range of paleolatitudes, from 35° to 60°N (Cecca, 1999). Despite the peculiar composition of the Late Jurassic molluscan assemblages, which include Boreal buchiids in association with Tethyan ammonites, they do not indicate an exact paleolatitude. Only the highest latitudes can be excluded in this case. However, the interval between 35° and 50°N appears to be most probable. In this interval exactly, the mixed Boreal–Tethyan molluscan assemblages of the Late Jurassic are encountered. Accordingly, we had to indicate localities of all findings in modern coordinates.

1.2. DISTRIBUTION AREAS OF MOLLUSCAN GENERA AND CONTROLLING FACTORS

Boreal–Tethyan migrations of Kimmeridgian to Valanginian mollusks took place within the Panboreal and Tethys–Panthalassa Superrealms (Westermann, 2000a, 2000b; Zakharov *et al.*, 2003; see Fig. 1). Whereas the Arctic taxa did not commonly penetrate into the Tethyan areas south of 30°N, the Tethyan forms or their descendants migrated as far north as 76°N. The water temperature lowering to the north was the major factor that controlled the dispersal of mollusks and other faunal groups in the Northern Hemisphere during the Late Jurassic–Early Cretaceous period, as it is evident

[2] In addition to eudemic ammonites, Fernández-López and Meléndez (1996) also recognize their miodemic (inhabitants not reproducing themselves in the habitat), parademic (specimens passively transported alive), and ademic (transported dead shells) forms.

Main localities of molluscan fauna analyzed in this work

Major localities (Realms) and their number		Sources
1	Ul'yanovsk Volga Realm	Mesezhnikov *et al.*, 1977; Blom *et al.*, 1984; *Unifitsirovannaya stratigraficheskaya...*, 1993; Rogov, 2001a, 2002
2	Kostroma Realm	Rogov, 2001a
3	Ural River basin	Ilovaiskii and Florenskii, 1941; Zakharov, 1981
4	Central Russia	Bogoslovskii, 1895; Zonov, 1937; Sazonova, 1971, 1977; Mesezhnikov *et al.*, 1979; Mesezhnikov, 1984; Baraboshkin, 1999
5	Caspian Sea Realm	Sasonova and Sasonov, 1983; Luppov *et al.*, 1986; Mesezhnikov, 1989
6	Northern Caucasus	Renz, 1904; Douvillé, 1910; Khimshiashvili, 1967; Sazonova, 1971; Khalilov *et al.*, 1974; Sey and Kalacheva, 1993;
7	Polar Ural Realm	Mesezhnikov, 1984; Bogomolov and Dzyuba, 1998
8	Barents Sea shelf	Basov *et al.*, 1989; Shul'gina and Burdykina, 1992
9	Pechora River basin	Mesezhnikov *et al.*, 1983; Mesezhnikov, 1984; Rogov, 2001a
10	Khatanga River basin	Saks *et al.*, 1969; Mesezhnikov, 1984; Shul'gina, 1985; Bogomolov, 1989
11	Paksa Peninsula	Shul'gina, 1985
12	Chukotka	Zakharov *et al.*, 1988
13	Tugurskii Bay, Uda River basin	Sey and Kalacheva, 1992
14	Southern Primor'e	Sey and Kalacheva, 1995, 1997
15	Northern Primor'e	Zakharov *et al.*, 1996; Sey and Kalacheva, 1999; Markovich *et al.*, 2000
16	Mangyshlak	Luppov *et al.*, 1983; Luppov *et al.*, 1986; Bogdanova *et al.*, 1989
17	Southern Karakum	*Nizhnii mel...*, 1985
18	Abkhazia	Khimshiashvili, 1989
19	Crimea	Yanin, 1970
20	Central Kopetdag	*Nizhnii mel...*, 1985
21	Kujawy	Kutek, 1994; Marek, Shul'gina, 1996
22	Rogosnik	Zakharov, 1981; Kutek and Wierzbowski, 1986
23	Bulgaria	Kutek, 1994
24	Spitsbergen	Zhirmunskii, 1927; Ershova, 1983; Shul'gina and Burdykina, 1992
25	Western Carpathians	Vašíček, Michalík, 1999
26	Switzerland	Atrops *et al.*, 1993
27	Southeastern France	Thieloy, 1973; Kemper *et al.*, 1981
28	Southern Germany	Atrops *et al.*, 1993; Schweigert, 1993, 1994; Scherzinger, Schweigert, 1999; Schweigert, Jantschke, 2001
29	Northern Germany	Kemper *et al.*, 1981; Kemper, 1987
30	Southern England	Casey, 1973; Casey *et al.*, 1977; Kemper *et al.*, 1981; Kelly, 1990
31	Southern Spain	Geyer, Olóriz Sáez, 1983
32	Eastern Greenland, Milne Land	Callomon, Birkelund, 1980; Rawson, 1981
33	Northern California	Imlay, 1961; Johnes *et al.*, 1969; Imlay, Johnes, 1970
34	Southern Alaska	Imlay, 1981
35	British Columbia	Frebold, 1964; Jeletzky, 1984; Poulton *et al.*, 1988; Hoedemaeker, 1991
36	Western Canada	Jeletzky, 1964
37	Western Mexico	Burckhardt, 1906; Imlay, 1980, 1984; Adatte *et al.*, 1994
38	Honshu Island	Sato, 1962, 1985; Takahashi, 1969
39	Hokkaido Island	Zakharov, 1981.

from the northward decrease of taxonomic diversity (Saks *et al.*, 1971). The northward water cooling is also confirmed by data of isotopic thermometry (Teis *et al.*, 1968; Ditchfield, 1997; and others). However, it is impossible to explain all changes in distribution area of a certain taxon from this general standpoint. Repeated invasions of Tethyan taxa to Boreal seas were not necessarily caused by the water temperature rise. The adaptive abilities of animals should be taken into consideration as well. Besides an insignificant water cooling, the other factor that stimulated mass invasions of some Arctic taxa into sub-Tethyan basins was a thermal tolerance of many Boreal species wider than that of Tethyan taxa.

Most of ammonite families were predominantly distributed within a single Superrealm or even Realm. For example, Oppeliidae and Craspeditidae are recognized as the Tethyan and Boreal-Arctic families, respectively. Sometimes however, distribution areas drastically changed, primarily those of Tethyan descendants. For instance, the Kimmeridgian genus *Suboxydiscites* (Oppeliidae), a descendant of Submediterranean *Ochetoceras* (Rogov, 2001b) or probably of *Oxycerites* (Schweigert and Jantschke, 2001), is characteristic mainly of the Arctic Realm (Mesezhnikov, 1984) of the Panboreal Superrealm.

Changes in habitat areas of mollusks could be associated with alteration of their way of living as well. The heteromorphic *Protancyloceras* dwelt almost exclusively in the Tethys, whereas their descendants, e.g., orthoconical *Bochianites* forms, were cosmopolitan. Limitation of *Protancyloceras* distribution areas by the Tethyan seas only can be explained by their epiplanktonic mode of life in the *Sargassum*–like algae mats (Barthel and Geyssant, 1973; Wierzbowski, 1990). At the same time, *Bochianites* and *Baculites* forms of similar morphology were able to migrate in the water column (Westermann, 1990; Tsujita and Westermann, 1998) and their distribution was limited primarily by the basin depth and, to a lesser degree, by the temperature. Therefore, the penetration of *Bochianites* into epicontinental seas of Europe and Siberia during the terminal Berriasian and Valanginian could be associated with the taxon ability to the dwelling in open basins. Another possible explanation is influence of the Boreal transgression that favored migration of *Bojarkia, Tollia, Neotollia*, and Cylindroteuthidae (belemnites) from high latitudes to 40°N in the East European and Chukotka–Canadian Provinces (Saks *et al.*, 1971).

Phylloceratida and Lytoceratida, excluding the relatively shallow-water Acolytoceratinae (Ziegler, 1981), are considered as oceanic cosmopolites, and their migration to the Arctic Realm, namely, to Greenland (Rawson, 1981) and northern Siberia (Bogomolov, 1989), was likely connected with the Boreal transgression and certain leveling of water temperatures in the Northern Hemisphere. The findings of phyllo– and lytoceratids in the upper Valanginian of Arctic Canada (Kemper, 1975) may also witness the widening connections with the ocean, but not the warming of Arctic waters. However, the temperature and currents were major factors restricting distribution of epicontinental ammonoids in contrast to their oceanic forms. The taxa relocation, excluding events of their migration, was commonly limited by Superrealm boundaries. For instance, circum-Boreal distribution areas are most characteristic of the Boreal-Arctic mollusks proper. Among ammonites, these are Kimmeridgian Cardioceratidae, Volgian Dorsoplanitinae, and Craspeditidae of the Volgian–Valanginian and, likely, of the early Hauterivian times. The Volgian belemnite subfamily Cylindroteuthinae was taxonomically most diverse within the Arctic areas north of 60°N, whereas Pachyteuthinae intensely diversified in low-boreal Realms south of 60°N (Saks *et al.*, 1971). Beginning from the Triassic, Buchiidae (bivalve mollusks) changed their circum-Pacific habitat for circum-Arctic seas. In the Late Jurassic and Early Neocomian, the southern boundary of their mass distribution approximately corresponded to the current parallel of 55°N. However, buchiids repeatedly migrated southward of this boundary, and sometimes, namely in the Volgian, late Berriasian and Valanginian times, they dispersed in abundance nearly to 40°N. Shortly before their extinction in the late Hauterivian, *Buchia* forms invaded North Western Europe (Zakharov, 1981; Kelly, 1990). All these invasions could be associated with lowering of the water temperature gradients during Boreal transgressions, because the Arctic cephalopods migrated southward concurrently with buchiids. In the Late Jurassic and Early Neocomian, bivalves Inoceramidae, the top-level sessile suspension feeders of moderately warm waters, were close to buchiids in the adaptation ability. They successfully competed with buchiids in relatively deep environments of the epicontinental Arctic seas (Zakharov and Turbina, 1979). In the Jurassic–Cretaceous boundary time, three inoceramid species (identification by Zakharov) known from the highly carbonaceous Bazhenov Formation (Volgian, Boreal Berriasian) that accumulated in a relatively deep-water epicontinental sea penetrated westward to the North Sea approximately to 52°N. We relate this migration directly with influx of the Arctic water mass to the south, down to the North England shores in the late Volgian–early Boreal Berriasian time.

Below we consider the mollusk migrations within substage intervals in each of three Realms mentioned above.

1.3. KIMMERIDGIAN–VALANGINIAN MOLLUSK MIGRATIONS

1.3.1. Early Kimmeridgian

Unlike the late Oxfordian, when the Boreal–Tethyan connections were rather limited, the initial Kimmeridgian was marked by intense multidirectional-migra-

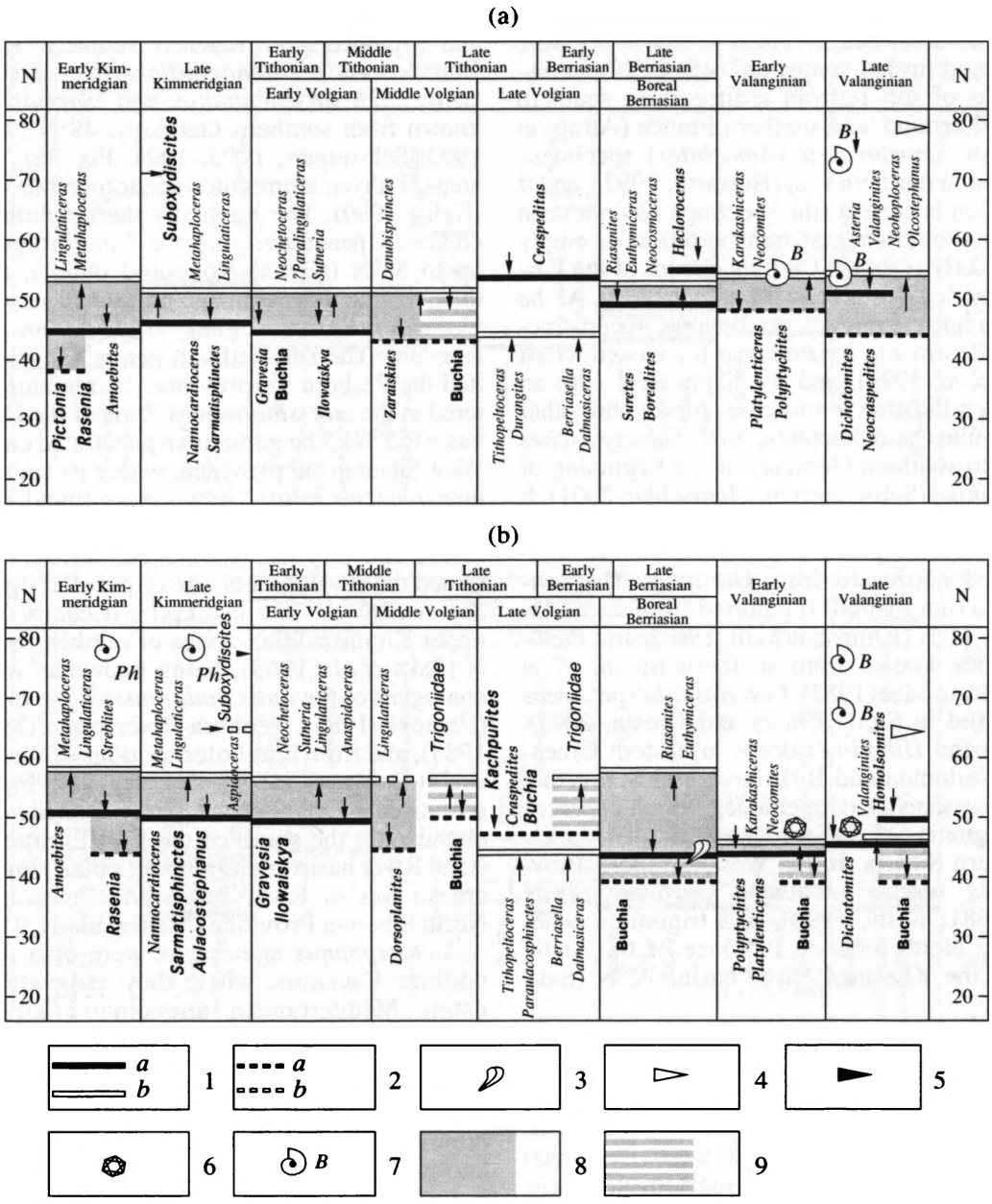

Fig. 3. Location of the Boreal–Tethyan ecotone and boundaries between the Panboreal and Tethys–Panthalassa Superrealms in the West (a) and East (b) European Provinces of the Boreal Atlantic Realm during the Kimmeridgian–Valanginian: (1–2) limits of Boreal (a) and Tethyan (b) expansion (1) or isolated "straying" (2); (3) coexisting rudists and Boreal ammonites; (4) coexisting Tethyan belemnites (*Hibolithes*) and Boreal ammonites; (5) Boreal belemnites Cylindroteutinae from low latitudes; (6) coexisting Hermatypic corals and Boreal ammonites; (7) oceanic high-latitude ammonites Phylloceratida (Ph), Lytoceratida (L) and *Bochianites*, Ammonitida, Perisphinctina (B); (8) ecotone of ammonite faunas; (9) ecotone of ammonites and bivalve mollusks.

Different fonts designate paleobiogeographic affinity of ammonites and bivalves as follows: *Glochiceras* if Tethyan, **Suboxydiscites** if Boreal descendant of Tethyan ancestor, ***Zaraiskites*** if low-boreal, and ***Surites*** if high-boreal (Arctic) ammonite genus; **Buchia**, if Boreal and *Trigoniidae* if Tethyan bivalve taxa.

tions within the Boreal Atlantic Realm (Fig. 3). A significant enlargement of ecotone area was recorded in the East European and especially in the West European Provinces. In the earliest Kimmeridgian (*densicostata/planula* Chrons), numerous Tethyan *Metahaploceras, Lingulaticeras* and, later, *Streblites* penetrated into the northern Poland and Russia (Figs. 3a, b). These taxa constitute a significant part of the ammonite assemblage from the basal Kimmeridgian of the Kostroma Realm (Rogov, 2001a). The Arctic subgenus *Amoeboceras* (*Amoebites*) concurrently migrated to the south. In some sequences of Poland, certain beds yield

shells of the last taxon representing up to 70% of the total ammonite assemblage. These ammonoids were also encountered further southward (45–47°N), in distribution areas of sub-Tethyan sediments in southern Germany, Switzerland, and southern France (Atrops *et al.*, 1993). An *Amoeboceras* (*Amoebites*) specimens was also found in northern Iraq (Howarth, 1992), and if its identification is correct (the specimen has not been pictured), we should suggest transportation of empty shells, most likely from the Caspian Realm of the East European Province, but not the taxon migration. At the same time, judging from the geodynamic reconstruction, the last Realm was located near the eastern coast of Africa (Cecca, 1999), and we likely deal with an inadequate identification in this case. Along with other Arctic ammonites and buchiids, first *Suboxydiscites* penetrated into southern Germany at the beginning of the Kimmeridgian (Schweigert and Jantschke, 2001). It is likely, however, that first representatives of the genus were relatively thermophilic, and later on their descendants migrated northward from Germany. The low-boreal *Rasenia* (not figured) is reported from the northern Caucasus, 44°N (Khimshiashvili, 1967), and *Pictonia* findings are known from southern Spain, 37°N (Geyer and Olóriz Sáez, 1983). Few *Rasenia* specimens were also found in Sicily (Pavia and Cresta, 2002). Submediterranean *Hibolithes* occur in eastern Greenland, 71°N (Callomon and Birkelund, 1980), together with first *Suboxydiscites* (Oppeliidae), which appeared here at the beginning of the late Kimmeridgian, earlier than in northern Siberia. In the West European Province, buchiids reached southern Germany, 48°N (Zakharov, 1981; Kelly, 1990), and trigoniids penetrated into the North Siberian Province of the Arctic Realm up to the Khatanga River basin, 72°N (Saks *et al.*, 1969).

In contrast, early Kimmeridgian faunas of the Boreal Pacific Realm were more isolated than those of the Oxfordian Age (Figs. 4a, 4b). Only buchiids migrated southward to Mexico, 30°N (Imlay, 1984). Data on *Amoeboceras* forms from western Mexico (Imlay, 1980) are published without their images. Reliable data on early Kimmeridgian mollusks from the Far East are unknown. Along the West Pacific coast, thermophilic ammonite genus *Taramelliceras* and Ataxioceratinae are unknown north of Japan (40°N; Sato, 1962; Takahashi, 1969).

1.3.2. Late Kimmeridgian

In the late Kimmeridgian, the character of ammonite migrations in the Boreal Atlantic Realm remained unchanged, but the Boreal-Atlantic and Boreal-Arctic molluscan assemblages became more contrasting than those of the early Kimmeridgian time (Saks *et al.*, 1971). The southward migration of Boreal Arctic ammonites somewhat weakened, but penetration of sub-Tethyan genera into Arctic seas became more distinct (Fig. 1). Within the West European Province, oppeliids migrated northward into the seas of Poland, and aspidoceratids reached southern England. The Boreal-Arctic *Nannocardioceras* and low-boreal *Gravesia, Aulacostephanus*, and *?Sarmatisphinctes* are known from southern Germany, 48°N (Atrops *et al.*, 1993; Schweigert, 1993, 1994; Fig. 3a). In the above areas, Tethyan ammonites occur together with buchiids (Kelly, 1990). The relatively thermophilic ammonites copiously penetrated into the East European Province up to 56°N (Nizhni Novgorod oblast), and some of them migrated even further northward, especially in the terminal Kimmeridgian *autissiodorensis* Chron (Fig. 3b). The sub-Tethyan genus *Aspidoceras* inhabited the Pechora subprovince. Its remains are encountered in the *autissiodorensis* Zone of the Pechora River basin (65°N). The genus also penetrated eastward in the West Siberian subprovince, where its species and *Sarmatisphinctes fallax* (Ilow.) were found in the Severnaya Sos'va River basin (Mesezhnikov, 1984; Bogomolov and Dzyuba, 1998)..The Arctic Realm represented the development site of peculiar oppeliid genus *Suboxydiscites*. The last taxon is characteristic of all upper Kimmeridgian zones of northern Siberia at 76° N (Saks *et al.*, 1969), being known as well from the analogues of the *autissiodorensis* Zone in Spitsbergen (Ershova, 1983), Pechora River basin (Mesezhnikov, 1984), and from boreholes sections of the Barents Sea shelf (Shul'gina and Burdykina, 1992; Fig. 5). Representatives of low-boreal genus *Aulacostephanus* are abundant in the south of the East European Province (Ural River basin and Orenburg oblast) and in the Severnaya Sos'va River basin and Polar Urals of the North Siberian Province (Mesezhnikov, 1984). Scarce *Aulacostephanus* specimens were also found in the northern Caucasus, where they associate with dominating Mediterranean ammonites (Khimshiashvili, 1967).

There are few reliable data on the upper Kimmeridgian sediments in the Boreal Pacific Realm. The joint occurrence of Boreal-Arctic and Tethyan forms is known only from northern California at 38°N, where *Amoeboceras* (*Amoebites*) and *Richeiceras* forms were found together with *Buchia* species (Imlay, 1961). *Pararasenia* forms occur in Mexico at 30°N (Burckhardt, 1906), but their age cannot be considered as exactly defined. According to Olóriz (1990), these ammonites are most likely not the true aulacostephanids and cannot be used for the Boreal–Tethyan correlation.[3] This conclusion seems to be rightful, as there are no related forms in Canada and Alaska (and in the Chukotka–Canadian Province as well), i.e., in the assumed migration way along the east-

[3] Hypothesis of Olóriz (1990) implying a decisive significance to colonization of epiplatform basins by ammonites whose oceanic ancestors developed in numerous parallel lineages is, in our view, insufficiently proved yet and does not explain all cases of their distribution. We believe that it is necessary to consider both possibilities: the distant migrations and the parallel development of similar features in different ammonite groups.

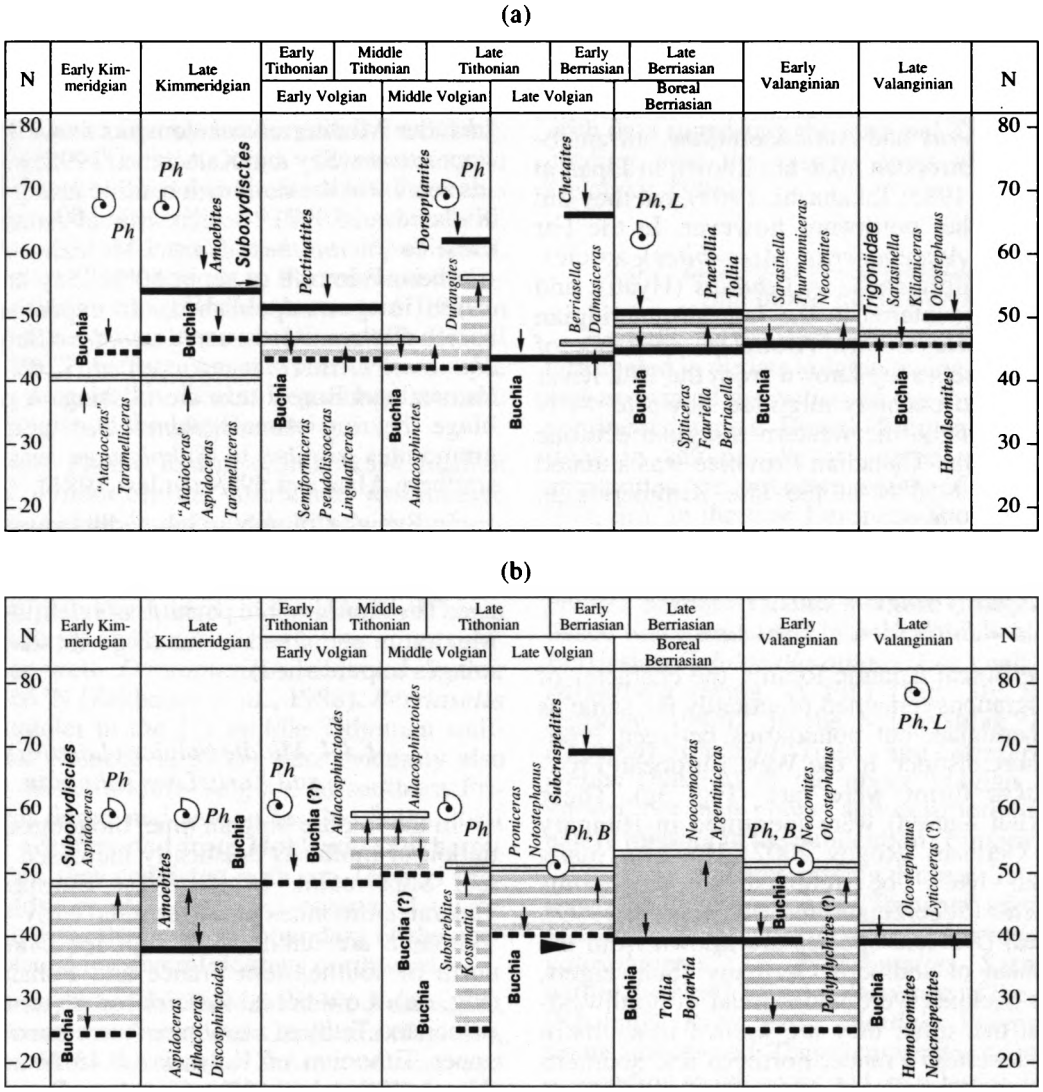

Fig. 4. Location of the Boreal–Tethyan ecotone and boundaries between the Panboreal and Tethys–Panthalassa Superrealms in the Boreal Pacific Realm during the Kimmeridgian–Valanginian (symbols as in Fig. 3).

ern coast of the Paleopacific. A possibility of migration through the Spanish corridor finds no support, because necessary forms are unknown from areas, through which the ammonite dispersal was to come about. It is likely that *Pararasenia* represents a descendant of the Tethyan *Idoceras* whose shells are abundant in older, lower Kimmeridgian sediments of Mexico. At the same time, it is also conceivable that the former genus is descendant of *Pictonia* whose remains are known from southern Spain (Geyer and Olóriz Sáez, 1983). The genus *Pararasenia* is therewith an endemic of the Caribbean Province, whereas the younger *"Pararasenia"* forms from Europe and Siberia can be attributed to the genus *Aulacostephanus*. Findings of *Buchia mosquensis* (von Buch) and *B. concentrica* (Sow.) from Mexico, 30°N (Burckhardt, 1906; Imlay, 1980), are most likely of the late Kimmeridgian age, though their images have not been published. In western Canada (49°N, British Columbia), Submediterranean genera *Lithacoceras, Discosphinctoides, Aspidoceras*, and *Suboxydiscites* occur in association (Fig. 4b) with scarce buchiids (Poulton *et al.*, 1988). The stratigraphic range of the assemblage is not strictly defined, but its late Kimmeridgian age can be assumed based on presence of *Lithacoceras* and *Discosphinctoides*. This is the only assemblage apart from the early Kimmeridgian fauna of southern Germany, where *Suboxydiscites* forms were encountered in association with Tethyan ammonites. The Canadian genus *Suboxydiscites* is likely somewhat older than the uppermost *mutabilis* Zone, during which it coexisted in northern Siberia and eastern Greenland with Arctic taxa. Another possible version is that *Suboxydiscites* migrated in British Columbia via cold bot-

tom current from the north with associated buchiids and Tethyan ammonites.

Exclusively Tethyan *Taramelliceras*, its species close to that of the lower Tithonian *T. (Fontannesiella)* included, *Aspidoceras* and Ataxioceratinae, all analogous to the West European taxa, are known in Japan at 40°N (Sato, 1962, 1985; Takahashi, 1969), but they did not penetrate further northward however. In the Far East only scarce *Amoeboceras (Amoebites)* species, similar to the Californian *A. (A.) dubius* (Hyatt), and buchiids were encountered in the late Kimmeridgian (Sey and Kalacheva, 1992). Arctic descendants of Tethyan *Suboxydiscites* are known from the Uda River basin at 55°N, and buchiids migrated down to 44°N (Fig. 4a). Accordingly, the western marginal ecotone area of the Chukotka–Canadian Province was situated between 45°N and 55°N in the late Kimmeridgian (Zakharov *et al.*, 1996).

1.3.3. Early Volgian–Early Tithonian and Early Middle Tithonian

Within the Boreal Atlantic Realm, the character of ammonite migrations remained practically the same as in the Kimmeridgian, but boundaries between Provinces were more distinct. In the West European Province, *Ilowaiskya* forms were rare (Fig. 3a). These ammonoids (not figured) were identified in Hungary and southern Germany (Rogov, 2002). However, many of them can likely be referred to the genus *Danubisphinctes* (Scherzinger and Schweigert, 1999). The low-boreal *Gravesia* species are known from the lowest Tithonian of southern Germany (Schweigert, 1993). Arctic buchiids were widespread in northwestern Europe at that time; they are known in southern England, northwestern France, northern and southern Germany, Austria, and Polish Carpathians, and have reached 48°N (Zakharov, 1981; Kelly, 1990; Kutek and Wierzbowski, 1986).

Tethyan *Neochetoceras, Lingulaticeras, Haploceras, Sutneria*, and *Anaspidoceras* are abundant in the Ul'yanovsk Realm of the East European Province (Fig. 3b). Lower Volgian *Neochetoceras, Sutneria*, and *Glochiceras* s.l. are known from central Poland. Low-boreal genus *Ilowaiskya* penetrated southward to 51°N (Orenburg Realm), where its species constitute the major part of the ammonite assemblage. Large accumulations of buchiids were found together with them in marly limestones (Zakharov, 1981).

New findings of supposedly Boreal-Arctic *Wheatleyites* were recently reported from the southern Tibet (Takei *et al.*, 2002). Judging from the reproduced pictures however, these ammonites represent more likely the Berriasian Berriasellidae.

In the Boreal Pacific Realm, the character of ammonite migrations markedly changed in the early Volgian (early Tithonian) as compared to that of the Kimmeridgian time. In circum-Pacific areas, Tethyan ammonites penetrated considerably further northward than in the Kimmeridgian. The ammonite assemblage from the Chukotka–Canadian Province (southern Primor'e)[4] is very similar to that of the South America, however it includes Mediterranean elements as well, especially in upper strata (Sey and Kalacheva, 1995; Fig. 4a). Buchiids represent the dominant benthic group here (Sey and Kalacheva, 1997). Scarce Boreal-Arctic ammonites close to *Pectinatites fedorovi* Mesezhn. were found in northern Primor'e at about 50°N (Sey and Kalacheva, 1999; images unpublished). In Japan at 39°N, only scarce Tethyan *Aulacosphinctoides* (Sato, 1985) and *Hybonoticeras* (Matsuoka *et al.*, 2002) forms are known, and Boreal taxa are missing. A poorer assemblage bearing *Aulacosphinctoides* and unidentified ammonites similar to *Subplanites* was recorded in southern Alaska at 59°N (Imlay, 1981).

In British Columbia, Submediterranean perisphinctids were found at 49°N (Poulton *et al.*, 1988) though the enclosing sediments can be of the Kimmeridgian age. The stratigraphic position of buchiids from central Mexico is undefined so far (Fig. 4b; Zakharov, 1981; images unpublished).

1.3.4. Middle Volgian–Late Middle and Early Late Tithonian

In the middle Volgian time, biogeographic differentiation of mollusks drastically increased in the Panboreal Superrealm. In the West European Province, Tethyan ammonites of the terminal early–initial middle Tithonian are unknown, except for *Danubisphinctes*, north of southeastern France and Polish Carpathians (Fig. 3a). Low-boreal *Zaraiskites regularis* Kutek and associated Tethyan ammonites were encountered in the upper Tithonian of Bulgaria at 43°N and in Poland (Kutek, 1994). In the West European Province, buchiids inhabited northwestern France, southern England, southern Poland, and Czechia (Zakharov, 1981; Kelly, 1990). The westward migrations of East European mollusks can likely be a reaction to stronger influence of the Boreal-Arctic water masses.

In the East European Province, Tethyan and Arctic ammonites coexisted during the *panderi* Chron only (Fig. 3b). *Haploceras, Sutneria*, and *Glochiceras* s.l. still occur, though being extremely scarce, in the lowermost *Panderi* Zone in the Ul'yanovsk Realm (Mesezhnikov *et al.*, 1977). *Haploceras* is also recorded in the uppermost *Panderi* Zone of the northern Caspian Realm (Mesezhnikov, 1989). Like *Anaspidoceras* of the terminal early Volgian time, these ammonites most likely penetrated into the Central Russian Sea from the

[4] Since the specific Tithonian–Neocomian ammonite assemblages of Primor'e strongly differ in composition and diversity from those of Chukotka and Arctic Canada, Sey and Kalacheva (personal communication, 2002) distinguished an independent Far East Province. Substantiated characteristic of the province are absent in their paper, and we use here the province name proposed by Saks *et al.* (1971).

south, and the Pripyat' strait was the only way for westward migrations of low-boreal ammonites (Rogov, 2002). Connections between Central Russian and North Caucasian basins are inferable based on of ammonites similar to *Dorsoplanites panderi* (d'Orb.), *D. dorsoplanus* (Vischn.), and *Lomonossovella lomonossovi* (Vischn.) found in the northern Caucasus at 44°N (Renz, 1904; Douvillé, 1910; Khimshiashvili, 1967). Pictures of two latter forms are unpublished. After the *panderi* Chron and up to the terminal early–initial late Berriasian time, Boreal-Arctic and Tethyan ammonites did not occur concurrently in the Boreal Atlantic Realm. Therefore, an ecotone of ammonite fauna was missing in this Realm beginning from the mid-middle Volgian to the late Berriasian.

In the Boreal Pacific Realm (Chukotka–Canadian Province and Primor'e), the ammonite assemblage analogous to that of the lower middle Tithonian supposedly existed to the terminal middle Tithonian or initial middle Volgian time (Fig. 4a). Scarce *Durangites* forms encountered slightly northward, in the Uda River basin at 55°N, were likely characteristic of the terminal middle Volgian as well. *Dorsoplanites* occurred further northward at 66°N (Zakharov *et al.*, 1988). *Berriasella* found by Khudolei in the (?) middle Tithonian sediments (Sey and Kalacheva, 1988) were evidently also characteristic of the middle Volgian. In southern Primor'e, buchiids dominated among benthic fauna; their remains were also reported from Hokkaido (Zakharov, 1981). In places, they coexisted with sub-Tethyan trigoniids (Zakharov *et al.*, 1996). As compared to the Kimmeridgian time, the northern boundary of the ecotone was displaced for several degrees northward.

In the eastern part of the Boreal Pacific Realm, i.e., in British Columbia and northern California (Fig. 4b), Tethyan ammonites *Kossmatia, Substeuroceras*, and *?Substreblites* were widespread in the late Tithonian corresponding most likely to the terminal middle Volgian (Zeiss, 1983, 1984).[5] Boreal-Arctic ammonites are represented in British Columbia (Canada, 52°N) by scarce specimens similar to *Titanites* forms (Frebold, 1964). The precise stratigraphic position of Canadian *"Titanites"* is not defined. It is likely that they are actually characteristic of the older, Kimmeridgian sediments (Hillebrandt *et al.*, 1992). Buchiids reached northern California to coexist there with Tethyan ammonites (Johnes *et al.*, 1969). The middle Volgian *Buchia mosquensis* (von Buch) and *B. rugosa* (Fischer) were reported (without images) from the beds in Mexico bearing *Durangites* (Imlay, 1980). However, stratigraphic range of *Durangites* in Mexico, as in Primor'e, is yet to be exactly defined in terms of the West European zonal succession, and it would be premature to make any reliable stratigraphic conclusions based on their findings. Imlay (1980) suggested that the *Durangites–Kossmatia* assemblage existed at the very beginning of the late Tithonian. His inference is compatible with data suggesting the terminal Tithonian episode of cooling near the eastern coast of the Paleopacific (Jeletzky, 1984).

1.3.5. Late Volgian–Terminal Late Tithonian and Initial Early Berriasian

Existence of the West European Province practically terminated in the late Volgian owing to a vast regression and associated deposition of the Purbeckian lagoonal-continental facies. Boreal–Tethyan ammonite migrations in Europe almost ceased, and Boreal-Arctic ammonites are unknown south of northern England (Fig. 3a). In the East European Province, *Craspedites* penetrated far southward, down to lower reaches of the Emba River in the Caspian Realm (47°N), where *Craspedites nodiger* (Eichw.) whose images are unpublished was encountered in association with typical early Berriasian *Calpionella alpina* (Lor.) and *Tintinopsella carpathica* (Murg. et Fil.) (Fig. 3b; Sasonova and Sasonov, 1983).[6] In the Mangyshlak, Boreal-Arctic *Kachpurites fulgens* (Traut.) and *Garniericeras? interjectum* (Nikitin) of the upper Volgian Substage are known, but their photos and descriptions are unfortunately missing in the publication (Luppov *et al.*, 1986).

In view of embarrassing Boreal–Tethyan connections, the identification of "Tethyan" ammonite genera *Aulacosphinctes, Berriasella, Lemencia*, and *"Virgatosphinctes"* (= *Praechetaites* Sasonova, 1979) within the North Siberian Province of the Arctic Realm (Khatanga River basin, Nordvik Peninsula, Fig. 5), seems unexpected. These ammonites occur in beds corresponding to the upper and, to a lesser degree, middle Volgian. Previously they were regarded as Tethyan genera (Shul'gina, 1967, 1985), but actually they most likely represent descendants of low-boreal ammonites (Zeiss, 1984; Kutek and Zeiss, 1988; Sey and Kalacheva, 1993). At least, the Siberian *"Berriasella"* shows the bidichotomous branching of ribs that is untypical of actual berriasellids. The ammonites have not been revised after the initial examination by Shul'gina. The new name *Praechetaites* was proposed only for *"Virgatosphinctes"* (Sasonova and Sasonov, 1979), and other forms of that peculiar ammonite assemblage should be reexamined.

In the Boreal Pacific Realm, the situation was practically unchanged. The association of Tethyan ammonites *Berriasella, Dalmasiceras, Proniceras, Spiticeras*, etc. and Boreal-Arctic buchiids is known in Primor'e, British Columbia, and northern California

[5] It is difficult to establish the exact age of *Kossmatia, Substeuroceras*, and *Parodontoceras* faunas from sections of California and British Columbia (see discussions in Jeletzky, 1984; Zeiss, 1984). In Mexico, representatives of these genera are known from both the upper Tithonian and lower Berriasian (Adatte *et al.*, 1994).

[6] The correlation potential of associated Boreal ammonites and calpionellids is moderately high, because diverse ranges of some species, e.g., of zonal *C. elliptica*, have been established in different provinces of the Tethys–Panthalassa Superrealm (Pessagno, written communication).

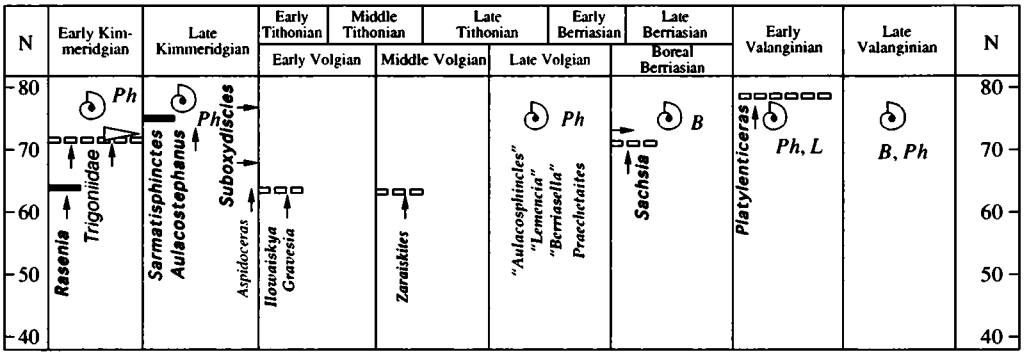

Fig. 5. Isolated "straying" events of Tethyan, low-boreal, and oceanic mollusks in the Arctic Realm during the Kimmeridgian–Valanginian (symbols as in Fig. 3).

(Fig. 4a; Johnes *et al.*, 1969; Imlay and Johnes, 1970; Sey and Kalacheva, 1999). In the northwestern Pacific coast, findings of ammonites are extremely scarce, and only the Arctic genus *Chetaites* was identified in Chukotka at 66°N (Zakharov *et al.*, 1988). Rare specimens of Arctic *Subcraspedites* were encountered in northern Canada (Jeletzky, 1984).

1.3.6. Boreal Berriasian–Terminal Early (?) and Late Berriasian

At the end of the Berriasian, transgression of Boreal seawaters is again recorded in North Western Europe. Rare findings of buchiids are known in Lincolnshire (England) and in the northern Jutland, Denmark (Kelly, 1990). Numerous Boreal-Arctic ammonites *Borealites, Surites*, etc., also occur in England, being though not associated with Tethyan forms (Casey, 1973). *Euthymiceras* and *Riasanites* penetrated to Poland most likely through the Central Russian sea (Fig. 3a). In Pomerania and Kujawy areas, the Rogozno Formation yields *Riasanites* forms in association with Tethyan ammonites *Himalayites* and *Picteticeras*, whereas *Euthymiceras* is found here together with Boreal-Arctic *Surites* and Tethyan *Neocosmoceras* (Marek and Shulgina, 1996).[7]

At the end of the early Berriasian, or most likely at the beginning of the late subage, Tethyan basins of the North Caucasian and Boreal seas of the East European Provinces were connected anew. The Boreal–Tethyan migrations ways were first opened for mollusks since the middle Volgian time. Tethyan ammonites *Euthymiceras* and *Riasanites* penetrated to the East European Province and Boreal-Arctic buchiids reached the North Caucasian seas (Fig. 3b; Sasonova, 1977; Sey and Kalacheva, 1993). In addition, scarce representatives of Boreal-Arctic *Surites* advanced down to the Belaya River basin in the northern Caucasus (Sasonova, 1971).

Boreal-Arctic mollusks are known from 44°N in the Mangyshlak, where rudists and Tethyan *Berriasella, Jabronella*, and *Mazenoticeras* occasionally coexisted with *Surites* and *Buchia*. (Luppov *et al.*, 1983; Bogdanova *et al.*, 1989). Buchiids penetrated even further southward, to 39°N in the southern Karakum area (*Nizhnii mel...*, 1985); their single findings are also known in the Crimea (Yanin, 1970). Presence of "*Hoplites* cf. *rjasanensis*" (images unpublished) has been once detected in Berriasian beds of Spitzbergen (Zhirmunskii, 1927), but this fact was not confirmed later on despite the intense investigations, and Shul'gina and Burdykina (1992) disputed a possibility of distinguishing the "*R. rjasanensis* beds" in Spitzbergen, as was proposed earlier by Ershova (1983). At the same time, some typical Boreal-Arctic ammonites, e.g., *Hectoroceras* and *Chetaites*, penetrated to the central Russian Sea (Sasonova, 1977; Mesezhnikov *et al.*, 1979); the latter has not been figured.

In the terminal Berriasian, cosmopolitan *Bochianites* and descendants of Tethyan *Sachsia sachsi* Schulgina penetrated from the Boreal Pacific to the Arctic Realm (Fig. 5; Shul'gina, 1985; Zakharov and Bogomolov, 1989). These peculiar berriasellids are morphologically similar to *Argentiniceras* cf. *noduliferum* described from the Berriasian of British Columbia (Jeletzky, 1984), and are likely descendants of this taxon.[8]

In the late Berriasian, the southern part of the Chukotka–Canadian Province (Primor'e) was inhabited by Tethyan ammonite genera (Fig. 4a). These are *Fauriella, Spiticeras*, and *Berriasella?* occurring in association with buchiids at 49°N (Zakharov *et al.*, 1996; Sey and Kalacheva, 1999; Markovich *et al.*, 2000). In Primor'e, the ecotone was displaced southward. Its northern boundary was at the parallel of 50°N owing to penetration of Boreal-Arctic ammonite genera *Tollia* and *Surites* to the south (Zakharov *et al.*, 1996). Associations of Tethyan ammonite assemblages and

[7] *Riasanites* specimens from Poland somewhat differ from those of central Russia; they are lacking grooves on the ventral side and show a relatively high position of the ribs branching points (Baraboshkin, 1999).

[8] According to Jeletzky (1984), the found *Argentiniceras* approximately correspond in age to the Berriasian *occitanica* Zone of Western Europe.

abundant benthic buchiids with the Boreal-Arctic *Bojarkia* and *Tollia* are also characteristic of the East Pacific coast (Fig. 4b; Johnes *et al.*, 1969; Imlay and Johnes, 1970; Zakharov, 1981; Shul'gina, 1985). *Neocosmoceras* and *Argentiniceras* were found in British Columbia at 51°N (Jeletzky, 1984; Hoedemaeker, 1991), and Boreal-Arctic *Surites* is known here slightly northward at 55°N (Jeletzky, 1964). It is important that the whole Berriasian of the Boreal Pacific Realm is characterized by a low taxonomic diversity and scarcity of Arctic ammonites (Zakharov and Bogomolov, 1989).

1.3.7. Early Valanginian

The early Valanginian marks a significant change in ammonite distribution in all three Realms. Beginning from the Valanginian, the ecotone of Boreal Atlantic Realm that hosted Boreal and Tethyan biotas extended considerably, and cross-migrations resumed (Fig. 3a). Numerous ammonites of the *Pseudogarnieria–Platylenticeras* group are known from northern Germany, Poland, Czechia (western Carpathians), France, England, European Russia, eastern Greenland, Spitzbergen, and Novaya Zemlya (images of fossils from the three latter Realms are unpublished). Boreal or Tethyan origin of these ammonites is disputable. They are interpreted as indicators of the Tethyan influence in northern Realms (Kemper *et al.*, 1981) and of Boreal impact in southern areas (Marek and Shulgina, 1996; Vašiček and Michalik, 1999). Some experts accepted their descent from the Tethyan Spiticeratinae (Kemper *et al.*, 1981; Kemper, 1987). Alternatively, it was suggested that these ammonites descended from craspeditids (Schindewolf, 1966; Shul'gina, 1985) that is confirmed by similar changes in their lobe lines during ontogeny. We prefer the latter standpoint, because the aforementioned character of the geographic distribution of ammonites in question likely indicates their low-boreal origin. Moreover, umbilical tubercles are characteristic not only of *Spiticeras* forms, but also of some late Volgian craspeditids and Valanginian polyptychitids. Thus, *Platylenticeras* forms found in Western Europe may indicate strengthening of Boreal influence at the beginning of the Valanginian. This is supported by joint occurrence of *Platylenticeras* and *Menjaites* in England (Casey *et al.*, 1977). It is strange, but according to Kelly (1990), buchiids are unknown in the Valanginian of Western Europe. In the second half of the early Valanginian the Boreal influence was still strong, and first polyptychitids penetrated into southeastern France exactly at that time (Shul'gina, 1985; Bogomolov, 1989). The Tethyan *Karakaschiceras* and *Neocomites* known from Poland (Marek and Shulgina, 1996) migrated to the north almost simultaneously with the Boreal-Arctic *Polyptychites* and low-boreal *Platylenticeras* (Fig. 3a). Sporadic penetrations of Tethyan *Neocomites* to England were likely associated with the early Valanginian transgression (Kemper *et al.*, 1981). On the other hand, these unique findings may also indicate the posthumous transportation of shells (Baraboshkin, 2001).

In the East European Province, Tethyan influence was almost intangible in the early Valanginian (Fig. 3b). Its only evidence in favor is the neocomitid species "*Hoplites* aff. *arnoldi* Kil." (TsNIGR Museum, no. 71/623) figured by Bogoslovskii (1895, Plate 4, figs. 7a–7c). This specimen is not yet precisely identified however. At the beginning of the Valanginian, low-boreal *Platylenticeras* penetrated from the East European Province to the Northern Caucasus (Khalilov *et al.*, 1974; images unpublished), and *Polyptychites* reached Mangyshlak at the same time. In the Arctic Realm, only Boreal taxa, but rare cosmopolites *Bochianites* and *Phylloceras*, existed in the Valanginian time (Fig. 5; Shul'gina, 1985).

The ecotone of the Chukotka–Canadian Province (Primor'e) was narrowed down to five degrees, being located between 51° and 46°N (Fig. 4a). Boreal-Arctic *Polyptychites* and *Neotollia* coexisted in the ecotone with Tethyan *Thurmanniceras, Neocomites, Olcostephanus, Sarasinella, Kilianella*, and *Neohoploceras* (Zakharov *et al.*, 1996; Sey and Kalacheva, 1989, 1999; Markovich *et al.*, 2000). Abundant *Buchia* remains occur in association with Tethyan ammonites in southern Primor'e. In northern California, comparatively diverse and numerous Boreal-Arctic ammonites *Tollia, Neotollia*, and *Polyptychites* are associated with Tethyan *Olcostephanus* and *Thurmanniceras* (Anderson, 1938; Imlay, 1984; Shul'gina, 1985). A single *Polyptychites* specimen was described even in Mexico (Burckhardt, 1906), but it may point to transportation of empty shells.

1.3.8. Late Valanginian

At the beginning of the late Valanginian, sea level rise recorded in the Northern Hemisphere, and influence of Tethyan fauna sharply increased in the West European Province. Abundant *Saynoceras, Bochianites, Valanginites, Olcostephanus, Karakaschiceras, Neohoploceras, Neocomites*, and *Sarasinella* appeared in England, Germany, and Poland (Figs. 3a, 3b).

The southward migrations of Boreal taxa became more intense concurrently with penetration of Tethyan forms into northern Europe at the beginning of the late Valanginian. For instance, Boreal-Arctic *Prodichotomites* are known from the lowermost upper Valanginian of western Carpathians (Vašiček and Michalík, 1997); *Dichotomites, Polyptychites, Prodichotomites*, and *Neocraspedites* are identified in northern and central Poland (Marek and Shulgina, 1996); and scarce *Prodichotomites* and *Dichotomites* occur in the upper Valanginian of France at 45°N (Thieloy, 1973; Besse *et al.*, 1986). Buchiids dwelt in the seas of North Western Europe (Kelly, 1990).

Through the seas of East European Province, polyptychitids penetrated southward down to the northern

margin of the Tethys–Panthalassa Superrealm and into the North Caucasian Province and Mangyshlak (44°N), where they coexisted with Tethyan ammonites of the genus *Valanginites* (Fig. 3b; Luppov *et al.*, 1983). The genus *Homolsomites* attributed to craspeditids is known from latitude of 49°N in the Caspian Realm (Shul'gina *et al.*, 1989). Buchiids and associated Tethyan genera *Valanginites, Neocomites,* and *Saynoceras* (*Nizhnii mel...*, 1985) migrated further to the south, to 38°N in the central Kopetdag. These migrations were triggered most likely by the decreased temperature gradient between the Panboreal and Tethys–Panthalassa biogeographic Superrealms.

In the second half of the late Valanginian, distribution areas of Boreal-Arctic polyptychitids, which were driven away to the north, sharply decreased in the West European Province (Kemper *et al.*, 1981), and Tethyan ammonites markedly enhanced their position. It is likely that we deal in this case with a northward displacement of boundary between the Panboreal and Tethys–Panthalassa Superrealms rather than with migration of certain ammonite group. The impact of warming is recorded not only in northern Europe but also in the Arctic Realm up to the Barents Sea plate, as it is evident from expansion of thermophilic foraminifers and from penetration of Tethyan belemnite genus *Hibolithes* into the Timan–Pechora basin (Mesezhnikov *et al.*, 1983; Basov *et al.*, 1989). The obvious predominance of Arctic ammonites in the East European Province indicates cessation of direct connection between the Central Russian and Polish basins at least in the late Valanginian. The only evidence in favor of strengthened Tethyan influence in the East European Province by the end of the Valanginian is the following statement of Zonov (1937, p. 45): "In the Neocomian sandy beds of the Russian Platform we encountered representatives of *Neocomites, Bochianites*, and other genera, and *Distoloceras* sp. in the Volga River basin." However, images and precise geographic and stratigraphic positions of ammonites remained unpublished, this considerably reduces value of this statement.

In the Boreal Pacific Realm, the ways of late Valanginian ammonite migrations were the same as in the early Valanginian, with the only difference: the Boreal influence slightly strengthened in the West Pacific coast, where dominating Tethyan ammonite genera *Olcostephanus, Sarasinella*, and *Kilianella* occur in association with Boreal-Arctic *Homolsomites* and buchiids (Fig. 4a; Zakharov *et al.*, 1996; Markovich *et al.*, 2000). On the contrary, the Boreal influence was somewhat reduced in the eastern coast (Fig. 4b). The Boreal-Arctic ammonites *Homolsomites, Neocraspedites* and bivalves *Buchia* did not penetrate southward of northern California, where they coexisted with Tethyan *Olcostephanus* and *Lyticoceras* (Johnes *et al.*, 1969; Imlay and Johnes, 1970; Zakharov, 1981; Shul'gina, 1985).

1.4. REGULARITIES IN MIGRATIONS OF KIMMERIDGIAN–VALANGINIAN MOLLUSKS AND POSITION OF BIOGEOGRAPHIC ECOTONE IN THE NORTHERN HEMISPHERE

In the Late Jurassic and Early Cretaceous, mollusks of the Northern Hemisphere were rather distinctly differentiated into Boreal taxa, which inhabited seas north of the 50°N, and Tethyan ones typical of the basins south of 45°N. A biogeographic ecotone existed between these latitudes in certain time spans and its basins experienced with time certain displacements in space.

New data obtained in last decades offer a possibility to establish more exactly the geographic position of boundaries of the Boreal–Tethyan ecotone in the Late Jurassic and early Neocomian, and to define the southern boundary of the Boreal Atlantic and Boreal Pacific Realms (Figs. 3, 4). Previously revealed time spans and events of Tethyan–Boreal and reverse migrations of molluscan assemblages or certain taxa are confirmed and new ones are established (Figs. 6, 7).[9] Kimmeridgian to Valanginian migrations of variable intensity are distinguishable in the Boreal Atlantic (West and East European Provinces), Boreal Pacific (Chukotka–Canadian and Boreal Pacific Provinces), and in Arctic (North Siberian Province) Realms. Mollusks, such as ammonites, belemnites, and bivalves, were divided into Tethyan (epicontinental sub-Tethyan forms included) and Boreal taxa. Among the latter, we discriminated more abundant Boreal-Arctic mollusks from low-boreal ones, many of which had Tethyan ancestors and were characteristic of the ecotone. It is interesting that during a considerably long time, from the second half of the late Volgian to the beginning of the Valanginian, when the ecotone ammonite fauna was either missing in Europe, or dwelt in places (in the late Berriasian), the low-boreal ammonites did not exist or occupied small distribution areas like that of the genus *Garniericeras* (Fig. 6b).[10] The genus *Platylenticeras* that descended from Arctic ancestors, though was of low-boreal type according to geographic distribution, appeared only at the beginning of the Valanginian. During the discussed time span, Boreal-Arctic buchiids reached the lowermost latitudes (30°N in the Boreal Pacific Province) only twice: in the early Kimmeridgian and late? Tithonian. In the West European Province they penetrated southward down to 48°N and reached 42–40°N in the East Europe only in the Berriasian and Valanginian. In the Boreal Pacific Realm, the Kimmeridgian–Valanginian buchiids constantly inhabited basins of the ecotone area down to latitudes of 42°N in the Chukotka–Canadian Province and of 38°N in the Boreal Pacific Province (Figs. 7a, 7b). In the North Siberian Province,

[9] For better clearness of Figs. 6 and 7, the Boreal scale of the East European Province was taken as a basis, and regional scales were preliminarily correlated with it.

[10] This taxon is absolutely unknown in the Boreal Pacific Realm.

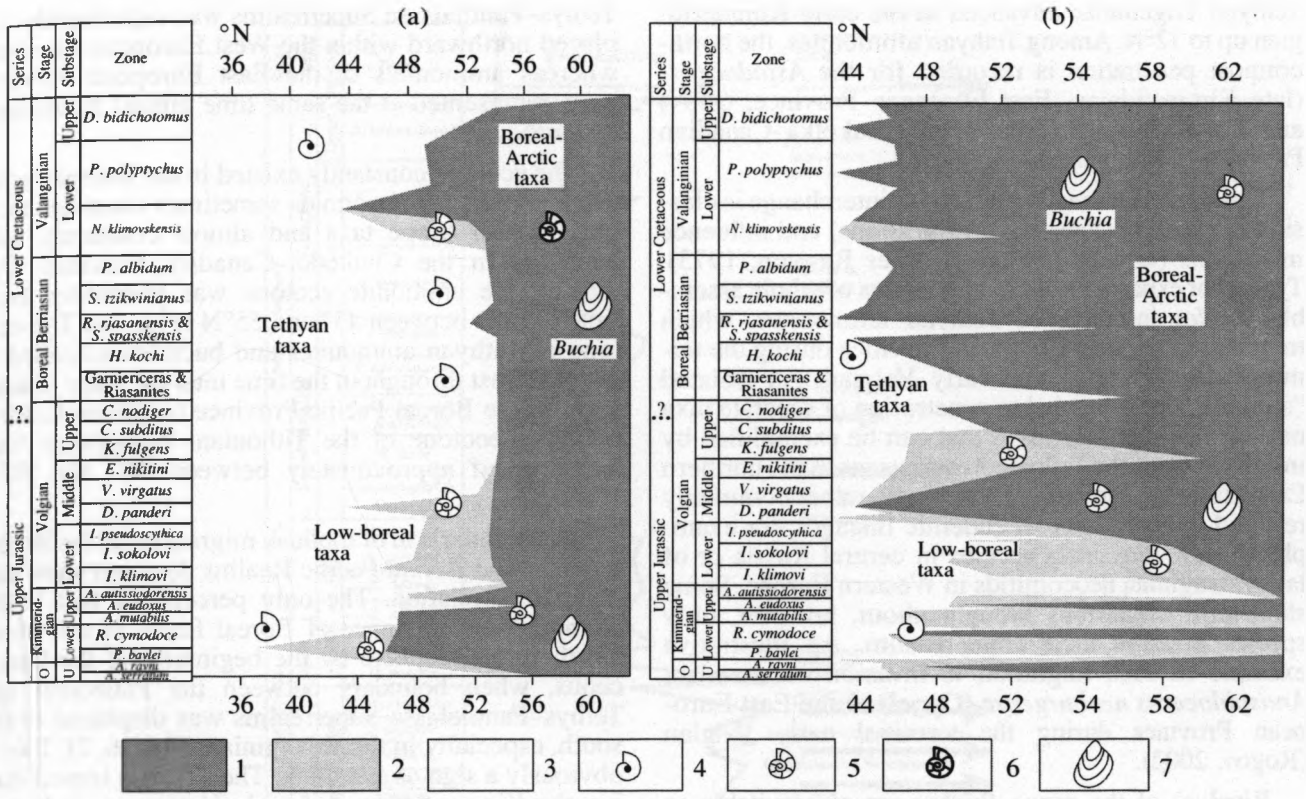

Fig. 6. Mollusk migrations within the Boreal–Tethyan biogeographic ecotone of the Boreal Atlantic Realm during the Kimmeridgian–Valanginian (basic scheme):
(1) Boreal taxa; (2) low-boreal taxa in Fig. 6 and *Buchia* in Fig. 7; (3) Tethyan taxa; (4) Tethyan ammonites; (5) low-boreal ammonites; (6) Boreal ammonites; (7) *Buchia*. Abbreviations in the stratigraphic columns: (u) upper; (O) Oxfordian; (Bor.) Boreal.

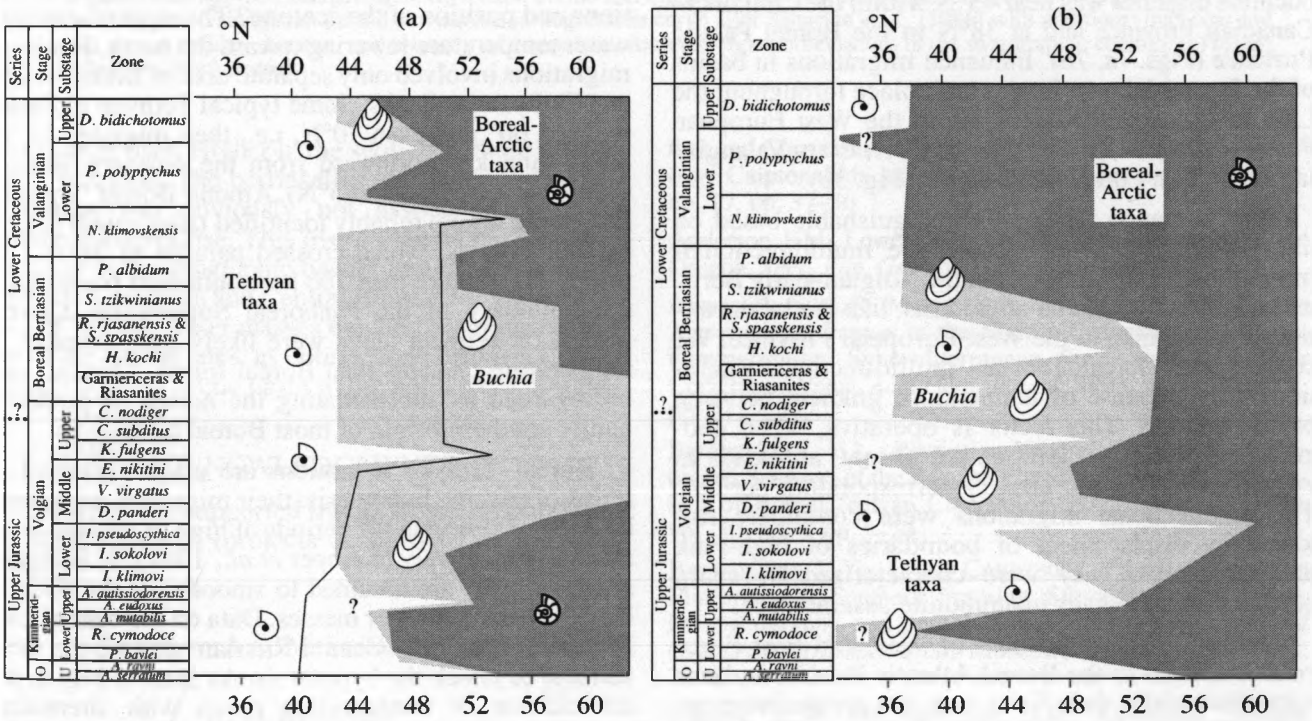

Fig. 7. Mollusk migrations within the Boreal–Tethyan biogeographic ecotone in the Boreal Pacific Realm during the Kimmeridgian–Valanginian (basic scheme; symbols as in Fig. 6).

Tethyan Trigoniidae advanced in the early Kimmeridgian up to 72°N. Among Tethyan ammonites, the northernmost penetration is recorded for the *Aspidoceras* (late Kimmeridgian, East European Province, 65°N) and *Durangites* (late Tithonian, Chukotka–Canadian Province, 54°N) genera.

In degree of intensity, the faunal interchange is classified into expansions (mass migrations) and influence migrations (isolated "straying" after Rawson, 1973). Typical of expansions were migrations of whole assemblages, for instance, of Tethyan ammonites, which migrated in the East European Province during the terminal Kimmeridgian and early Volgian. An isolated "straying" corresponded to penetration of separate taxa or their few representatives that can be exemplified by immigration of the Tethyan *Aspidoceras* to the northern East European Province. Expansions rather commonly resulted in appearance of endemic lineages, for example, of new *Riasanites* species in central Russia or of late Valanginian neocomitids in Western Europe. Some short-term expansions brought about, however, only species invasion their home Realm. An illustrative example of such migration is invasion of abundant *Anaspidoceras neoburgense* (Oppel) in the East European Province during the terminal early Volgian (Rogov, 2002).

Bivalves of the genus *Buchia* are also suitable to demonstrate the intensity of migrations. Their expansions were characteristic of the entire Kimmeridgian–Valanginian in the Boreal Pacific Realm. Beginning from the middle Volgian, the northern boundary of buchiids dispersal was near 43°N within the Chukotka–Canadian Province and at 38°N in the Boreal Pacific Province (Figs. 7a, 7b). Influence migrations in basins of the Boreal Atlantic Realm took place throughout the Late Jurassic–early Neocomian in the West European Province (Fig. 3a) and during the Berriasian–Valanginian in the East European Province (Fig. 3b).

Two migration types are distinguishable based on directions of taxa ways. These are multidirectional-migrations, for instance that in the Volgian–early Berriasian, and unidirectional migrations, like that of the terminal Valanginian in the West European Province. We connect the Boreal–Tethyan multidirectional-migrations with decrease of temperature gradient between paleozoochores. This factor is operative, when geographic barriers to migration are absent, and leads to expansion of ecotone area in corresponding periods. The unidirectional migrations were commonly followed by displacement of boundaries of high-rank paleozoochores. They were characterized by sharp compositional changes in ammonite assemblages.

Despite the close position of West and East European Provinces in the Boreal Atlantic Realm, mollusk migrations within their limits were not always interconnected that may be explained by influence of currents and geographic barriers. In the terminal Valanginian, for example, the boundary between Panboreal and Tethys–Panthalassa Superrealms was significantly displaced northward within the West European Province, whereas ammonites of the East European Province were represented at the same time almost exclusively by Arctic taxa.

The ecotone constantly existed in the Boreal Pacific Realm. Tethyan ammonoids sometimes coexisted there with Boreal-Arctic taxa and almost constantly with buchiids. In the Chukotka–Canadian Province (Primor'e), the ammonite ecotone was positioned from time to time between 45° and 55°N (Fig. 7a). The ecotone of Tethyan ammonites and buchiids extended to 43°N almost throughout the time interval under discussion. In the Boreal Pacific Province (northern California), the ecotone of the Tithonian–Valanginian time was located approximately between 40° and 50°N (Fig. 7b).

The comparison of mollusk migrations in the Boreal Atlantic and Boreal Pacific Realms does not show any distinct correlation. The only perceptible fact is the strengthening influence of Boreal fauna in the whole Northern Hemisphere by the beginning of the Cretaceous, when boundary between the Panboreal and Tethys–Panthalassa Superrealms was displaced to the south, especially in the Valanginian (Figs. 6, 7). This is obviously a sign of evolution. The Tethyan impact during the Kimmeridgian and early Volgian periods was well pronounced only in the Boreal Atlantic Realm, where "migration waves" are recorded (Fig. 6). It was less distinct in the Boreal Pacific Realm (Fig. 7).

What factors influenced the Boreal–Tethyan migrations and position of the ecotone? The major factor was water temperature lowering toward the north. However, migrations involved only separate taxa of Boreal-Arctic and Tethyan mollusks. Some typical Tethyan mollusks reached 60° and even 70°N, i.e., they migrated for 2–3 thousand km northward from the northern Tethys–Panthalassa boundary (45°N). Among Boreal "wanderers," there are no reliably identified (illustrated) genera of cephalopods, which crossed parallel of 38°N, i.e., migrated for more than 700 km southward from southern boundary of the Panboreal Superrealm. Certain groups of Tethyan fauna were likely more tolerant to temperature changes than Boreal forms. This fact can be regarded as substantiating the notion of predominantly southern origin of most Boreal taxa.

Boreal–Tethyan migrations are often explained in terms of eustatic hypothesis: their migration ways must be open or closed in the periods of high or low sea-level stands, respectively (Kemper *et al.*, 1981). In addition, sea level rises are assumed to smooth out the thermal barriers between water masses. Data on the central East European Province (Central Russian sea) are the most suitable to check the hypothesis. As seen in Fig. 8, the coincidence of transgression peaks with alternating ammonite migrations is observable only within the Kimmeridgian–middle Volgian period, when northward migrations of Tethyan ammonites were coeval to

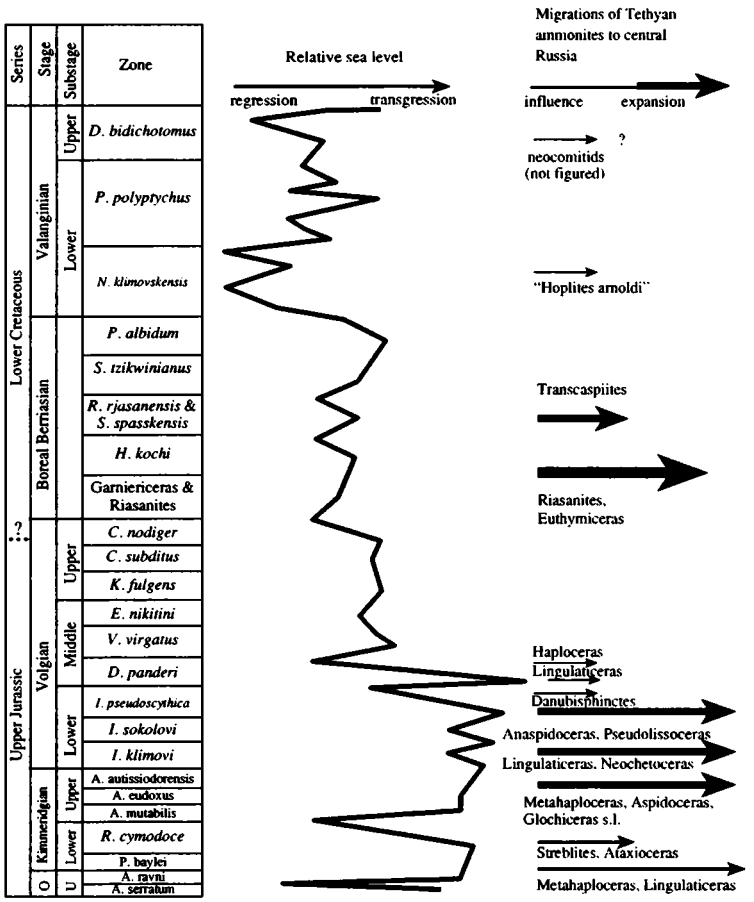

Fig. 8. Correlation between transgression–regression events and migrations of Tethyan ammonites into the Central Russian Sea in the Kimmeridgian–Valanginian period (transgression–regression curve after Sahagian *et al.*, (1996) with additions; thickness and length of arrows indicate duration and intensity of migrations, respectively). Abbreviations in the stratigraphic column: (u) upper; (O) Oxfordian; (Bor.) Boreal.

the sea level rises. Higher in the sequence, there is nothing of this kind. The berriasellid expansion during the Berriasian was obviously not associated with the eustatic sea-level rise. This event may be explained by breakage of the geographic barrier that existed between the North Caucasian and Central Russian seas. The influence of Tethyan water masses evidently dominated over that of the Boreal ones, as connections between Central Russian Sea and Arctic basin in the north were limited.

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Biostratigraphic Zonation of the Upper Cretaceous in the East European Platform

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Abstract—Two biostratigraphic zonations, one based on macrofauna (primarily on inocerams and belemnites) and the other one based on microfossils, mostly on benthic foraminifers, are distinguished in the regional scale of the Upper Cretaceous of the East European platform. Both zonations are correlated to each other and with the Global Upper Cretaceous Scale (Olfer'ev and Alekseev, 2002).

Key words: Upper Cretaceous, zonation of macrofauna and benthic foraminifers, correlation, East European platform.

INTRODUCTION

In 2001, the Interdepartmental Stratigraphic Committee of Russia authorized the Regional Stratigraphic Scale of the Upper Cretaceous in the East European platform after its preliminary consideration at the regional conference held January 12, 2001. The scale has not been characterized so far in publications and cannot be properly used in practice of geological survey and relevant works. Accordingly, the main objective of this communication is to present in a brief manner the biostratigraphic zonations included in the scale. Characterization of superhorizons and horizons will be published elsewhere.

Ammonites are extremely rare in the Upper Cretaceous of the Russian plate, where concurrent planktonic foraminifers are of provincial character and rock sequences reveal stratigraphic ranges of calcareous nannoplankton index species, which differ from those in the Mediterranean region. Owing to these peculiarities, it is impossible to use directly the Global Upper Cretaceous Scale suggested recently (Olfer'ev and Alekseev, 2002) in practice of dating and correlation of regional stratigraphic subdivisions. That is why the regional biostratigraphic scheme appears to be necessary.

The first regional biozonation of the Upper Cretaceous in the East European platform was elaborated in 1954 (*Resheniya...*, 1955). To a considerable extent, it was based on macrofauna zonation established long ago by Arkhangel'skii (1912) in Upper Cretaceous sequences of the Volga River basin (Table 1). In the Cenomanian Stage, Arkhangel'skii distinguished the lower *Exogyra conica* and *Actinocamax primus* zones, and the *Lingula krausei* Beds above them. He correlated the *Inoceramus brongniarti* Zone with the lower Turonian Substage and attributed barren Cretaceous strata to the upper Turonian. The *Inoceramus involutus* Zone was regarded as corresponding to the Emscherian (Coniacian) Stage, whereas the Senonian interval was divided into the *Inoceramus pachti, Pteria tenuicostata, Belemnitella mucronata*, and *Belemnitella lanceolate* zones.

The scheme of 1954 was based on paleontological characterization of Upper Cretaceous sequences in eastern, western, and southern areas of the Russian plate. In addition to inocerams and belemnites, it accounted for distribution of ammonites found shortly before by Mikhailov (1951) in Campanian and Maastrichtian strata of the Donetsk basin and western Ukraine. The *Neohibolites ultimus, Pecten asper, Acanthoceras rhotomagense*, and *Actinocamax plenus* zones were established in the Cenomanian Stage. Distribution of inocerams was used to subdivide the Turonian–Coniacian–lower Santonian interval into the *Inoceramus labiatus, I. lamarcki, I. involutus*, and *I. cardissoides* zones (from the base upward). The *Oxytoma tenuicostata* Zone divided into the lower *Stensioeina exculpta–Anomalina stelligera* and upper *Ataxophragmium orbignynaeformis* foraminiferal subzones (?) was attributed to the upper Santonian. The lower Campanian Substage was divided into the *Gonioteuthis quadrata* and *G. mammillata* zones, and the upper one included the *Hoplitoplacenticeras coesfeldiense* and *Belemnitella mucronata* zones. The *Bostrychoceras polyplocum* and *Belemnitella langei* zones were distinguished in the lower Maastrichtian Substage, while the *Discoscaphites constrictus* corresponded to the upper Maastrichtian. The last zone was additionally divided into the *Acanthoscaphites tridens, Belemnitella lan-*

ceolate, Pachydiscus neubergicus, and *Belemnitella americana* subzones. Remarkable in the scheme was discrimination of foraminiferal subzones in the *Oxytoma tenuicostata* Zone (Table 1).

The scale of 1954 was modernized in 1959 (Naidin, 1960; *Resheniya...*, 1962), though its essence remained unchanged. In the renewed version, subdivision of Santonian, Campanian, and Maastrichtian stages was based on belemnites studied by Jeletzky (1948, 1951, 1955, 1958) and Naidin (1951, 1952, 1954, 1956). Versions of the scale published later on were supplemented with data on faunal assemblages from the Crimea, which turned out to be here more diverse within some intervals than in concurrent strata of the platform (Gerasimov *et al.*, 1962; Naidin, 1969).

At present, the former scales based on zonation of macrofauna find a limited application, because the main distribution area of Upper Cretaceous deposits is concealed, as drilling results showed, under younger sediments. Correlation and subdivision of borehole sections can be substantiated by microfossils only, and zonation of benthic foraminifers gained the prime importance for the situation we have now in the East European platform.

After insignificant corrections, biostratigraphic schemes elaborated by Naidin *et al.*, (1984a, 1984b, 1986) have been used in this work as a basis for the suggested regional zonal scale (Table 2).

GEOGRAPHIC LIMITATIONS

The zonal scale described below is applicable to southern areas of the Russian plate, where the widespread Upper Cretaceous deposits accumulated in a vast, relatively shallow basin, one in a system of sea basins, which represented the northern periphery of the Tethys. We mean primarily those areas, which lie inside the territory of the Russian Federation.

In terms of structural geology, the study region comprises a southern part of the Moscow syneclise, the Voronezh anteclise, the southwestern sector of the Volga–Ural anteclise with an internal Ul'yanovsk–Saratov depression, and the northwestern margin of the circum-Caspian depression (Fig. 1).

In terminology of Naidin *et al.*, (1986), the region under consideration represents a part of the European paleobiogeographic province (EPP) corresponding to southern and temperate (partially) latitudinal zones of Europe. In other words, it may be termed as a part of low- or sub-Boreal zone. Since the Late Cretaceous climate was warmer than now, environments in the concurrent sea basin of the East European platform corresponded to those of either the subtropical or, most likely, temperate zone.

On the east, the EPP southern boundary was situated to the south of the Crimea and northern Caucasus. Inside the EPP, there can be distinguished several subprovinces separated by sublatitudinal boundaries, which controlled distribution of belemnites, ammonites, and other invertebrates. For instance, Christensen (1990) distinguished the northerly Central Russian and southerly Central European subprovinces of the EPP. The analyzed region corresponded almost entirely to the northern part of the EPP, i.e., to the Central Russian subprovince. Marine biota that populated the region was of a rather monotonous composition in all the areas from the west to the east, and this situation is favorable for elaboration of a uniform biozonation. Despite its remoteness, the Kaliningrad area was also a part of the subprovince.

The Moscow syneclise is a particular case however, because benthic fauna from this structure is impoverished, mostly represented by inoceramids. Foraminifers and single ammonite and belemnite remains occur here at discrete levels, while radiolarians represent the main group of nannoplankton. Accordingly, our zonal scale is valid only for the Cenomanian, Turonian, and basal Coniacian intervals of the Upper Cretaceous sequence in the Moscow syneclise. It is clear that the Late Cretaceous biota of this syneclise included many taxa in common with biota of the Timan–Pechora province (Marinov *et al.*, 2002), where an independent biostratigraphic scheme should be elaborated.

ZONATION OF MACROFAUNA

According to Naidin *et al.* (1986, p. 14) "it is reasonable to distinguish chronozones in the European paleobiogeographic province, which can be based on ammonites and inocerams for the Cenomanian, on inocerams for the Turonian and Coniacian, on inocerams and belemnites for the Santonian, and on belemnites and ammonites for the Campanian and Maastrichtian." This alternation of guide fossil groups reflects their relative importance in separate intervals of the sequence that was controlled by the global biota evolution, on the one hand, and by changes in concrete paleogeographic environments, on the other. In other words, it is historical–geological in essence. Unfortunately, the Upper Cretaceous deposits of the Russian platform are almost lacking ammonites, single finds of which are only fragmentary described in publications. Thus, the ammonite scale proper cannot be used in the study region.

Cenomanian. The *Schloenbachia varians–Turrilites costatus* Zone corresponds in range to the lower–basal middle Cenomanian and is correlative with two lower Cenomanian zones of the western Kazakhstan (*Stratigraficheskie...*, 1996). *Turrilites costatus* Lam., the last of two ammonite index species, is unknown in the platform, whereas *Schloenbachia varians* (J. Sow.) occurs quite frequently in platform deposits (Arkhangel'skii, 1912, 1922, 1926; Milanovskii, 1940; Gerasimov *et al.*, 1962; Lavrova, 1971; Glazunova, 1972; Naidin, 1974). Exactly the distribution interval of *Schloenbachia varians* defines stratigraphic range of the zone, because this form appears simultaneously with *Mantelliceras man-*

Table 1. Correlated stratigraphic schemes of Upper Cretaceous deposits in central and southeastern areas of the East European platform and in some adjacent regions

Global Upper Cretaceous Scale (Olfer'ev and Alekseev, 2002)					Biozonation of the Upper Cretaceous in the Saratov and Penza areas of the Volga River basin (Arkhangel'skii, 1912)			Unified stratigraphic schemes of Upper Cretaceous deposits in the Russian platform of 1954 and 1958				Stratigraphic scheme of Upper Cretaceous deposits in the Russian platform (Naidin, 1960; Gerasimov *et al.*, 1962)				Upper Cretaceous biozonation in the Russian platform and Crimea (Najdin, 1969)		
System	Series	Stage	Substage	Zone or Subzone	Stage	Substage	Zone	Stage	Substage	Zone		Stage	Substage	Zone	Subzone	Stage	Substage	Zone or Subzone
Cretaceous	upper	Maastrichtian	upper	*Anapachydiscus terminus*	Senonian	upper	*Belemnitella americana*	Maastrichtian	upper	*Discoscaphites constrictus*	*Pachydiscus neubergicus Belemnitella americana B. arkhangelskii* [1958]	Maastrichtian	upper	*Belemnella arkhangelskii*	*Belemnitella nowaki*	Maastrichtian	upper (*Belemnella arkhangelskii* Beds)	
				Anapachydiscus fresvillensis														
			lower	*Pachydiscus epiplectus*			*Belemnitella lanceolata*				*Acanthoscaphites tridens Belemnitella lanceolata*		lower	*Belemnella lanceolata*	*Belemnella sumensis*		lower (*Belemnitella lanceolate* Beds)	*Belemnella lanceolata*
				Pseudokossmaticeras tercense														
		Campanian	upper	*Nostoceras hyatti*			Siliceous clay barren of fossils			?					*Belemnella licharewi*			*Belemnella licharewi*
				Didymoceras donezianum					lower	*Bostrychoceras polyplocum Belemnitella langei*		Campanian	upper	*Belemnella langei*			upper	*Belemnitella langei*
				Bostrychoceras polyplocum														
				Hoplitoplacenticeras marroti			*Belemnitella mucronata*	Campanian	upper	*Hoplitoplacenticeras coesfeldiense Belemnitella mucronata* [1954] *B. m. senior* [1958]				*Belemnitella mucronata senior*				*Belemnitella mucronata senior*
			lower	*Delawarella campaniensis*					lower	*Gonioteuthis quadrata Gonioteuthis mammillata* [1954]			lower	*Gonioteuthis quadrata* (S) *Belemnitella mucronata alpha* (N)			lower	*Gonioteuthis quadrata*
				Placenticeras bidorsatum			?			?					*Oxytoma tenuicostata*			*Oxytoma tenuicostata u Micraster schroederi*
			upper	*Placenticeras polyopsis* / *Placenticeras planum*		lower	*Pteria tenuicostata*		upper	*Oxytoma tenuicostata*	*Ataxophragmium orbignynaeformis*					Santonian	upper (*Gonioteuthis granulata* Beds)	
											Stensioeina exsculpta [1954] *Anomalina stelligera*			*Gonioteuthis granulata* (S)				
			lower	*Texanites gallicus*			*Inoceramus pachti*		lower	*Inoceramus cardissoides*				*Inoceramus cardissoides*			lower (*Inoceramus cardissoides* Beds)	

Upper Cretaceous biozonation in the East European platform (Naidin and Kopaevich, 1977)			Upper Cretaceous biozonation in the East European paleobiogeographic province (Naidin *et al.*, 1984b, 1986)			Boreal standard of the Upper Cretaceous (Zakharov *et al.*, 1987)		Regional stratigraphic scheme of western Kazakhstan, Santonian–Maastrichtian (*Stratigraficheskie...*, 1996); Stratigraphy of the Mangyshlak Mts., Cenomanian–Coniacian (Marcinowski *et al.*, 1996)			Regional stratigraphic scheme of Upper Cretaceous deposits in the Russian platform (approved by the ISC Bureau, February 2, 2001)			
Stage	Substage	Zone or Subzone	Stage	Substage	Zone or Subzone	Zone or Subzone		Stage	Substage	Zone or Subzone	Zone or Subzone		Substage	Stage
Maastrichtian	upper	*Neobelemnella kazimiroviensis* (=*Belemnella arkhangelskii*) / *Belemnitella junior*	Maastrichtian	upper	*Neobelemnella kazimiroviensis*	*Neobelemnella kazimiroviensis*		Maastrichtian	upper	*Neobelemnella kazimiroviensis*	*Hoploscaphites constrictus* / *Belemnitella junior – Neobelemnella kazimiroviensis*		upper	Maastrichtian
	lower	*Acanthoscaphites tridens* / *Belemnella sumensis*		lower	*Acanthoscaphites tridens* / *Belemnella sumensis*	*Acanthoscaphites tridens* / *Belemnella sumensis*			lower	*Belemnella sumensis*	*Acanthoscaphites tridens* / *Belemnella sumensis*		lower	
		Belemnella lanceolata			*Belemnella lanceolata*	*Belemnella lanceolata*				*Belemnella lanceolata*	*Belemnella lanceolata*			
		Belemnella licharewi			*Belemnella licharewi*	*Belemnella licharewi*				*Belemnella licharewi*	*Belemnella licharewi/Micraster grimmensis*		upper	Campanian
Campanian	upper	*Belemnitella langei* / *Belemnitella langei najdini*	Campanian	upper	*Belemnitella langei* / *Belemnitella langei najdini*	*Belemnitella langei*		Campanian	upper	*Belemnitella* ex gr. *langei* / *Belemnitella langei najdini*	Belemnitella langei / *Belemnitella langei najdini/Micraster grimmensis*			
		Belemnitella langei langei			*Belemnitella langei langei*					*Belemnitella langei langei*	*Belemnitella langei langei/Didymoceras donezianum*			
		Belemnitella langei minor			*Belemnitella langei minor*					*Belemnitella langei minor*	*Belemnitella langei minor/Bostrychoceras polyplocum*			
		Hoplitoplacenticeras coesfeldiense			*Belemnitella mucronata mucronata* and *Hoplitoplacenticeras coesfeldiense*	*Belemnitella mucronata*				*Hoplitoplacenticeras coesfeldiense* and *Belemnitella mucronata mucronata*	*Hoplitoplacenticeras coesfeldiense/Belemnitella mucronata mucronata*			
	lower	*Gonioteuthis quadrata gracilis* and *Belemnellocomax mammillatus*		lower	*Gonioteuthis quadrata gracilis* and *Belemnellocamax mammillatus*	*Gonioteuthis quadrata gracilis*			lower	*Gonioteuthis quadrata gracilis* and *Belemnellocamax mammillatus*	*Belemnellocamax mammillatus*		lower	
		Gonioteuthis quadrata quadrata and Belemnitella mucronata alpha			*Gonioteuthis quadrata quadrata* and *Belemnitella mucronata alpha*					*Gonioteuthis quadrata quadrata* and *Belemnitella mucronata alpha*	*Belemnitella mucronata alpha*			
		Actinocamax laevigatus and *Belemnitella praecursor mucronatiformis*			*Actinocamax laevigatus* and *Belemnitella praecursor mucronatiformis*. *Pteria* Beds of the East European platform	*Gonioteuthis quadrata quadrata* / *Actinocamax laevigatus*				*Actinocamax laevigatus* and *Belemnitella praecursor mucronatiformis*	*Belemnitella praecursor mucronatiformis*			
Santonian	upper	*Gonioteuthis granulata* and *Inoceramus patootensis*	Santonian	upper	Gonioteuthis granulata and Inoceramus patootensis	*Gonioteuthis granulata*		Santonian	upper	*Gonioteuthis granulata*	*Sphenoceramus patootensis/Belemnitella praecursor praepraecursor*		upper	Santonian
	lower	*Inoceramus cardissoides*		lower	*Inoceramus cardissoides*; *Inoceramus undulatopicatus* at the base	*Sphenoceramus cardissoides*			lower	*Inoceramus cardissoides* [Str.] *Sphenoceramus pachti Cladoceramus undulatoplicatus* [Mar.]	*Texanites texanus/Sphenoceramus cardissoides/Belemnitella propinqua propinqua*		lower	

Table 1. (Contd.)

Global Upper Cretaceous Scale (Olfer'ev and Alekseev, 2002)					Biozonation of the Upper Cretaceous in the Saratov and Penza areas of the Volga River basin (Arkhangel'skii, 1912)			Unified stratigraphic schemes of Upper Cretaceous deposits in the Russian platform of 1954 and 1958			Stratigraphic scheme of Upper Cretaceous deposits in the Russian platform (Naidin, 1960; Gerasimov *et al.*, 1962)				Upper Cretaceous biozonation in the Russian platform and Crimea (Najdin, 1969)		
System	Series	Stage	Substage	Zone or Subzone	Stage	Substage	Zone	Stage	Substage	Zone	Stage	Substage	Zone	Subzone	Stage	Substage	Zone or Subzone
Cretaceous	upper	Coniacian	upper	*Paratexanites serratomarginatus*	Emscherian		?	Coniacian		?			?				?
			middle	*Gauthiericeras margae*			*Inoceramus involutus*		upper	*Inoceramus involutus*	Coniacian		*Inoceramus involutus*		Coniacian		upper (*Inoceramus involutus* Beds)
				Peroniceras tridorsatum			Barren Cretaceous			? [1954] / *Inoceramus wandereri* [1958]			*Inoceramus wandereri*				lower (*Inoceramus wandereri* Beds)
			lower	*Forresteria (Harleites) petrocoriensis*					lower	Undetected index species							
		Turonian	upper	*Subprionocyclus neptuni*	Turonian					?			?				?
				Romaniceras deverianum													
			middle	*Romaniceras ornatissimum*			*Inoceramus brongniarti*	Turonian	upper	*Inoceramus lamarcki* (*Inoceramus falcatus*?) [1958]	Turonian	upper	*Inoceramus lamarcki*		Turonian	upper (*Inoceramus lamarcki* Beds)	
				Romaniceras kallesi													
				Kamerunoceras turoniense													
				Calligoniceras woollgari													
			lower	*Mammites nodosoides*					lower	*Inoceramus labiatus*		lower	*Inoceramus labiatus*			lower (*Inoceramus labiatus* Beds)	
				Watinoceras coloradoense													
				Pseudaspidoceras flexuosum													
				Watinoceras devonense						?			?				*Actinocamax plenus triangulus*

Upper Cretaceous biozonation in the East European platform (Naidin and Kopaevich, 1977)			Upper Cretaceous biozonation in the East European paleobiogeographic province (Naidin *et al.*, 1984b, 1986)			Boreal standard of the Upper Cretaceous (Zakharov *et al.*, 1987)	Regional stratigraphic scheme of western Kazakhstan, Santonian–Maastrichtian (*Stratigraficheskie...*, 1996); Stratigraphy of the Mangyshlak Mts., Cenomanian–Coniacian (Marcinowski *et al.*, 1996)			Regional stratigraphic scheme of Upper Cretaceous deposits in the Russian platform (approved by the ISC Bureau, February 2, 2001)		
Stage	Substage	Zone or Subzone	Stage	Substage	Zone or Subzone	Zone or Subzone	Stage	Substage	Zone or Subzone	Zone or Subzone	Substage	Stage
?			?			*Volviceramus involutus*	Coniacian	upper	*Magadiceramus subquadratus*	*Magadiceramus subquadratus*	upper	Coniacian
Coniacian	upper	*Inoceramus involutus*	Coniacian	upper	*Inoceramus involutus*			middle	*Volviceramus involutus/Volviceramus koeneni*	*Volviceramus involutus*	middle	
	lower	*Inoceramus wandereri*		lower	*Inoceramus schloenbachi*			lower	*Cremnoceramus crassus/Cremnoceramus deformis*	*Volviceramus koeneni*		
?			?			*Inoceramus schloenbachi*			*Cremnoceramus brongniarti*	*Cremnoceramus crassus–Cremnoceramus deformis* *Cremnoceramus brongniarti*	lower	
									Cremnoceramus rotundatus	*Cremnoceramus rotundatus*		
Turonian	upper	*Inoceramus woodsi*	Turonian	upper	*Inoceramus costellatus* and *Inoceramus striatoconcentricus*	*Inoceramus costellatus*	Turonian	upper	*Mytiloides incertus*	*Mytiloides scupini–Mytiloides incertus*	upper	Turonian
									Inoceramus costellatus	*Mytiloides striatoconcentricus* *Inoceramus costellatus*		
		Inoceramus lamarcki			*Inoceramus lamarcki*; *Inoceramus apicalis* at the base	*Mytiloides labiatus*		middle	*Inoceramus lamarcki*	*Inoceramus lamarcki*	middle	
									Inoceramus apicalis	*Inoceramus apicalis*		
	lower	*Inoceramus labiatus*		lower	*Inoceramus labiatus* and *Inoceramus hercynicus*				*Mytiloides hercynicus*	*Mytiloides subhercynicus–Mytiloides hercynicus*		
								lower	*Mytiloides labiatus* *Mytiloides kossmati*	*Mytiloides labiatus – Mytiloides kossmati*	lower	
									Watinoceras amudariense/Mytiloides hattini			
		Preactinocamax plenus triangulus			*Preactinocamax plenus triangulus*	?	?			*Preactinocamax plenus triangulus*		

Table 1. (Contd.)

Global Upper Cretaceous Scale (Olfer'ev and Alekseev, 2002)					Biozonation of the Upper Cretaceous in the Saratov and Penza areas of the Volga River basin (Arkhangel'skii, 1912)			Unified stratigraphic schemes of Upper Cretaceous deposits in the Russian platform of 1954 and 1958			Stratigraphic scheme of Upper Cretaceous deposits in the Russian platform (Naidin, 1960; Gerasimov *et al.*, 1962)				Upper Cretaceous biozonation in the Russian platform and Crimea (Najdin, 1969)		
System	Series	Stage	Substage	Zone or Subzone	Stage	Substage	Zone	Stage	Substage	Zone	Stage	Substage	Zone	Subzone	Stage	Substage	Zone or Subzone
Cretaceous	upper	Cenomanian	upper	*Nigericeras scotti*	Cenomanian	lower	*Lingula krausei* Beds	Cenomanian	upper	?	Cenomanian	upper	?	*Actinocamax plenus*	Cenomanian	upper	*Scaphites aequalis*
				Neocardioceras juddii						*Acanthoceras rhotomagense* *Scaphites aequalis* [1958] *Actinocamax plenus* [1954]			*Scaphites aequalis* (S) [1958]				
				Metoicoceras geslinianum													
				Calycoceras guerangeri													
			middle	*Alternacanthoceras jukesbrownei*													
				Acanthoceras rhotomagense / *Turrilites acutus*													
				Acanthoceras rhotomagense / *Turrilites costatus*													
			lower	*Mantelliceras dixoni*					lower	*Neohibolites ultimus* *Pecten asper* [1954] *Actinocamax plenus* [1958]		lower	*Exogyra conica*			lower	
				Mantelliceras mantelli / *Mantelliceras saxbii*			*Exogyra conica*							*Actinocamax primus*			
				Mantelliceras mantelli / *Sharpeiceras schlueteri*													
				Mantelliceras mantelli / *Neostlingoceras carcitanense*													

Note: (1) In the third column, years in square brackets after the taxon name mean one of two references given in the column heading. (2) Empty cells with question marks correspond to intervals undistinguished in corresponding schemes as individual stratigraphic subdivisions. Some of them have been implicitly regarded as continuations of adjacent zones.

telli (J. Sow.) and has its evolutionary termination in the *Turrilites costatus* Subzone.

The zone is an equivalent of *Neohibolites ultimus* and *Praeactinocamax primus primus* beds of the belemnite scale and corresponds in range to the lower Cenomanian Substage in the Upper Cretaceous stratigraphic scale for the Russian platform of 1958. The same correlation between the indicated subdivisions is established as well in northwestern Germany (Christensen *et al.*, 1992). Except for Ostreidae, belemnites represent fossils most widespread in Cenomanian deposits of the platform, which enable the stage identification. It should be mentioned, however, that *Neohibolites ultimus* (Orb.) has not been confidently detected in the platform, whereas in the Crimea Mountains it is characteristic of the terminal lower–middle Cenomanian strata (Naidin *et al.*, 1975; Alekseev, 1989). *Neohibolites* forms represent the belemnite group that is more thermophilic than *Belemnitella* species, the Cenomanian *Actinocamax* forms of the Central Russian subprovince included.

Inoceramus crippsii Mant. is an inoceramid form characteristic of the zone in question, but this taxon is known only beyond limits of the region under consideration.

Acanthoceras rhotomagense–Inoceramus crippsii Zone. Extremely rare ammonite specimens have been found in the higher interval of the middle Cenomanian Substage. Single finds of *Acanthoceras rhotomagense* (Brgt.) from the Voronezh area (Semenov, 1986) imply that sedimentary sections of the Russian plate may include the synonymous zone established in western Europe. Tröger (1981) pointed out that *Inoceramus crippsii* Mant. still exists at this level. Stratigraphic range of this taxon extends up to the middle–upper Cenomanian boundary (Atabekyan, 1994).

Inoceramus pictus pictus–Praeactinocamax plenus longus Zone. Macrofossils are very rare in the upper

Upper Cretaceous biozonation in the East European platform (Naidin and Kopaevich, 1977)			Upper Cretaceous biozonation in the East European paleobiogeographic province (Naidin *et al.*, 1984b, 1986)				Boreal standard of the Upper Cretaceous (Zakharov *et al.*, 1987)		Regional stratigraphic scheme of western Kazakhstan, Santonian–Maastrichtian (*Stratigraficheskie...*, 1996); Stratigraphy of the Mangyshlak Mts., Cenomanian–Coniacian (Marcinowski *et al.*, 1996)			Regional stratigraphic scheme of Upper Cretaceous deposits in the Russian platform (approved by the ISC Bureau, February 2, 2001)		
Stage	Substage	Zone or Subzone	Stage	Substage	Zone or Subzone		Zone or Subzone		Stage	Substage	Zone or Subzone	Zone or Subzone	Substage	Stage
?			?									Mytiloides hattini		
Cenomanian	upper	*Scaphites aequalis*	Cenomanian	upper	*Sciponoceras gracile*; *Inoceramus pictus bohemicus–Praeactinocamax plenus plenus* Beds in Mangyshlak		*Praeactinocamax plenus triangulus*		Cenomanian	upper	*Neocardioceras juddii*	*Inoceramus pictus bohemicus*	upper	Cenomanian
							Sciponoceras gracile				*Actinocamax plenus*	*Inoceramus pictus pictus/Praeactinocamax plenus longus*		
					Eucalycoceras pentagonum		*Eucalycoceras pentagonum*							
				middle	*Inoceramus crippsii*	*Alternacanthoceras jukesbrownei*	*Alternacanthoceras jukesbrownei*			middle	*Acanthoceras jukesbrownei*	*Acanthoceras rhotomagense/Inoceramus crippsii*	middle	
						Turrilites acutus	*Turrilites acutus*				*Acanthoceras rhotomagense*			
						Turrilites costatus	*Turrilites costatus*	*Inoceramus crippsii*				*Turrilites costatus – Schloenbachia varians/Praeactinocamax primus primus – Neohibolites ultimus/Inoceramus crippsii*		
	lower	*Neohibolites ultimus*		lower		*Mantelliceras mantelli and Schloenbachia varians*	*Mantelliceras mantelli*			lower	*Mantelliceras dixoni*		lower	
		Parahibolites tourtiae									*Mantelliceras mantelli*			

Cenomanian Substage. Single specimens of *Praeactinocamax plenus longus* Najd. found in the East European platform imply that we may have here a subdivision analogous to the *Praeactinocamax plenus* Zone of western Kazakhstan and correlative with the *Inoceramus pictus* Zone distinguished by Wright *et al.* (1984) in western Europe. According to Marcinowski *et al.* (1996), the *plenus* Beds of Mangyshlak correspond to the *Calycoceras guerangeri* and *Metoicoceras geslinianum* zones of the ammonite scale. Consequently, the subdivision under consideration may be tentatively correlated with two lower zones of the upper Cenomanian accepted in the general scale. We should mention as well that *Praeactinocamax plenus* (Blainv.) has been found only in the *Metoicoceras geslinianum* Zone of western Europe. According to Marcinowski and his colleagues, the upper boundary of *Praeactinocamax plenus* Zone coincides with the first occurrence level of ammonites *Neocardioceras juddii* (Barr. et Guerne) in the Mangyshlak (Table 3).

Inoceramus pictus bohemicus Zone. This zone corresponds to the higher upper Cenomanian interval representing terminal portion of this substage (Tröger, 1981). In the regional scheme elaborated for the East European platform, we correlated this subdivision with the *Neocardioceras juddii* Zone of the general ammonite scale, although Naidin (*Stratigraficheskie...*, 1996) assumed that *Inoceramus pictus bohemicus* Leonhard represents subspecies characteristic of the entire upper Cenomanian of western Kazakhstan. Christensen *et al.* (1992) placed the lower boundary of the same inoceramid zone at the base of the *Metoicoceras geslinianum* Zones of the ammonite scale accepted in northwestern Germany.

Mytiloides hattini Zone. The regional scale of the Cenomanian Stage is crowned by the *Mytiloides hattini* Zone of inoceramids that has been established in the Pueblo section of the United States (Walaszczyk, 1992; Kennedy *et al.*, 2000), where it corresponds to the *Nigericeras scotti* Zone of the ammonite standard. The *Mytiloides hattini* interval zone comprises beds

Table 2. Stratigraphic scheme of Upper Cretaceous deposits in the East European platform

General stratigraphic scale							Regional stratigraphic subdivisions				
System	Series	Stage	Substage	Zone or subzone of ammonite scale	Zone of planktonic foraminifers	Nannoplankton zonation (Perch-Nielsen, 1985)	Superhorizon, horizon		Molluscan and echinoderm regional zone or subzone	Zone of benthic foraminifers	Subzone or beds with benthic foraminifers
Cretaceous	upper	Maastrichtian	upper	*Anapachydiscus terminus*	*Abathomphalus mayaroensis*	CC26 *Nephrolithus frequens*	Severskii	Sudzha	*Hoploscaphites constrictus* / *Belemnitella junior–Neobelemnella kazimiroviensis*	*Brotzenella praeacuta–Hanzawaia ekblomi*	
				Anapachydiscus fresvillensis		CC25 *Arkhangelskiella cymbiformis* c / b					
			lower	*Pachydiscus epiplectus*	*Gansserina gansseri*	a			*Acanthoscaphites tridens* / *Belemnella sumensis*	*Brotzenella complanata*	*Bolivinoides draco draco*
						CC24 *Reinhardtites levis*					
				Pseudokossmaticeras tercense		CC23 b			*Belemnella lanceolata*		*Brotzenella complanata*
					Globotruncana aegyptiaca					*Neoflabellina reticulata*	
		Campanian	upper	*Nostoceras hyatti*	*Globotruncanella havanensis*	*Tranolithus phacelosus* a		Tereshkino	*Belemnella licharewi/Micraster grimmensis*	*Angulogavelinella gracilis*	
									Belemnitella langei / *Belemnitella langei najdini/Micraster grimmensis*	*Globorotalites emdyensis*	*Brotzenella taylorensis*
				Didymoceras donezianum	*Globotruncanita calcarata*	CC22 *Quadrum trifidum*		Maslovo	*Belemnitella langei langei/Didymoceras donezianum*		*Bolivinoides draco miliaris*
				Bostrychoceras polyplocum	*Globotruncana ventricosa*	CC21 *Quadrum nitidum* / CC20 *Ceratolithoides aculeus*			*Belemnitella langei minor/Bostrychoceras polyplocum*		*Globorotalites emdyensis*
				Hoplitoplacenticeras marroti	*Globotruncanita elevata*	CC19 *Calculites ovalis*			*Hoplitoplacenticeras coesfeldiense/ Belemnitella mucronata mucronata*	*Brotzenella monterelensis*	
			lower	*Delawarella campaniensis*		CC18 *Aspidolithus parcus*		Alekseevka	*Belemnellocamax mammillatus* / *Belemnitella mucronata alpha*	*Cibicidoides temirensis*	*Cibicidoides aktulagayensis* / *Cibicidoides temirensis*
				Placenticeras bidorsatum			Shilov	Dubenki	*Belemnitella praecursor mucronatiformis*	*Gavelinella clementiana clementiana*	
		Santonian	upper	*Placenticeras polyopsis*	*Dicarinella asymetrica*	CC17 *Calculites obscurum*			*Sphenoceramus patootensis/Belemnitella praecursor praepraecursor*	*Gavelinella stelliger*	*Stensioeina pommerana* Beds
				Placenticeras paraplanum		CC16 *Lucianorhabdus cayeuxii*		Podgorenskii			
			lower	*Texanites gallicus*		CC15 *Reinhardtites anthophorus*		Terepsha	*Texanites texanus/Sphenoceramus cardissoides/Belemnitella propinqua propinqua*	*Gavelinella infrasantonica*	

Table 2. (Contd.)

General stratigraphic scale							Regional stratigraphic subdivisions				
System	Series	Stage	Substage	Zone or subzone of ammonite scale	Zone of planktonic foraminifers	Nannoplankton zonation (Perch-Nielsen, 1985)	Superhorizon, horizon		Molluscan and echinoderm regional zone or subzone	Zone of benthic foraminifers	Subzone or beds with benthic foraminifers
Cretaceous	upper	Coniacian	upper	*Paratexanites serratomarginatus*	*Dicarinella concavata*	CC14 Micula staurophora	Gubkin	Vol'sk	*Magadiceramus subquadratus*	*Gavelinella thalmanni*	
			middle	*Gauthiericeras margae*					*Volviceramus involutus*		
				Peroniceras tridorsatum					*Volviceramus koeneni*		
			lower	*Forresteria (Harleites) petrocoriensis*		CC13 Marthasterites furcatus			*Cremnoceramus crassus – Cremnoceramus deformis*	*Gavelinella kelleri*	
									Cremnoceramus brongniarti		
									Cremnoceramus rotundatus		
		Turonian	upper	*Subprionocyclus neptuni*		CC12 Lucianorhabdus maleformis		Bannovo	*Mytiloides scupini – Mytiloides incertus*	*Gavelinella moniliformis*	
				Romaniceras deverianum					*Mytiloides striatoconcentricus*		
			middle	*Romaniceras ornatissimum*	*Marginotruncana sigali*	CC11 Quadrum gartneti			*Inoceramus costellatus*		
				Romaniceras kallesi	*Helvetoglobotruncana helvetica*				*Inoceramus lamarcki*		
				Kamerunoceras turoniense					*Inoceramus apicalis*		
			lower	*Mammites nodosoides*					*Mytloides subhercynicus – Mytloides hercynicus*	*Gavelinella nana*	
				Watinoceras coloradoense					*Mytloides labiatus – Mytloides kossmati*		
				Pseudaspidoceras flexuosum							
				Watinoceras devonense					*Praeactinocamax plenus triangulus*		
		Cenomanian	upper	*Nigericeras scotti*	*Whiteinella archaeocretacea*	CC10 Microrhabdulus decoratus	Bryansk	Dyat'kovo	*Mytiloides hattini*	*Lingulogavelinella globosa*	
				Neocardioceras juddii					*Inoceramus pictus bohemicus*		
				Metoicoceras geslinianum	*Rotalipora cushmani*				*Inoceramus pictus pictus/Praeactinocamax plenus longus*		
				Calycoceras guerangeri							
			middle	*Alternacanthoceras jukesbrownei*					*Acanthoceras rhotomagense/Inoceramus crippsii*		
				Acanthoceras rhotomagense							
				Turrilites acutus							
				Turrilites costatus	*Rotalipora reicheli*						
			lower	*Mantelliceras dixoni*	*Rotalipora globotruncanoides*	CC9 Eiffellithus turriseiffelii		Polpino	*Turrilites costatus – Schloenbachia varians/Praeactinocamax primus primus – Neohibolites ultimus/Inoceramus crippsii*	*Gavelinella cenomanica*	
				Mantelliceras mantelli							
				Mantelliceras saxbii							
				Sharpeiceras schlueteri							
				Neostlingoceras carcitanense							

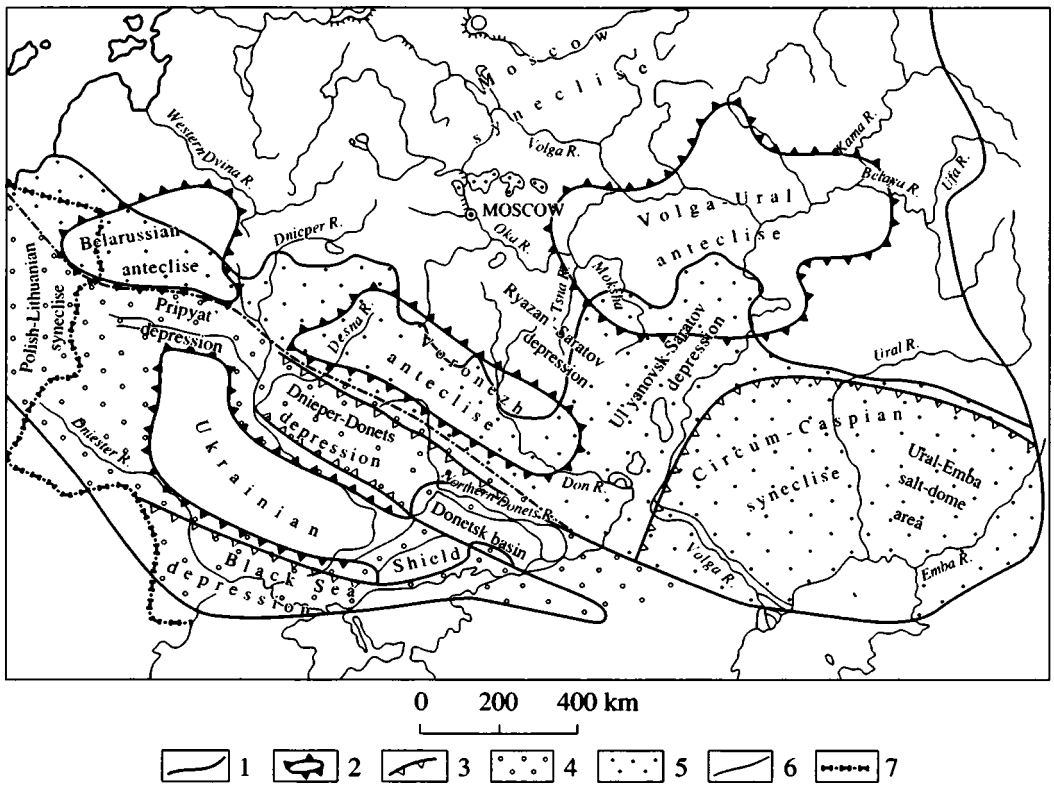

Fig. 1. Distribution areas of Upper Cretaceous deposits in different structures of the Russian platform (after Naidin *et al.*, 1986) and paleogeographic zoning of the Late Cretaceous time (after Christensen, 1990): (1) the Russian platform boundary; (2) shield or anteclise; (3) syneclise or depression; (4) Central European and (5) Central Russian paleobiogeographic subprovinces; (6) present-day distribution limits of Upper Cretaceous deposits; (7) state boundary of the former USSR.

between the first occurrence levels of *Mytiloides hattini* Elder and *Mytiloides puebloensis* Wal., the last of which marks the base of the overlying zone. Biozone of *Mytiloides hattini* Elder is actually much wider, because this species existed in Europe and America even during the Turonian time. This situation engendered the erroneous idea that the *Mytiloides hattini* Zone corresponds in Mangyshlak to the Turonian *Watinoceras coloradoense* Zone of the ammonite scale (Marcinowski *et al.*, 1996) or to the basal Turonian of Poland (Walaszczyk, 1992) (Table 3). Strictly speaking, this particular zone is most likely unrecorded over the greater part of the Russian plate, where hiatus between Cenomanian and Turonian stages is usually very distinct: various horizons of the lower and middle Cenomanian are overlain here by terminal lower or middle Turonian beds. We included this subdivision in our scheme in order to retain the necessary succession. Moreover, it seems to be recognizable in some sections. For instance, the middle–upper Cenomanian Melovatka Formation of the Saratov area yields nannoplankton of the 10 zone (unpublished data of M.N. Ovechkina), and Kopaevich detected planktonic foraminifers of the *Whiteinella archaeocretacea* Zone in upper beds of that formation.

Turonian Stage. Praeactinocamax plenus triangulus Zone. According to Naidin *et al.* (1986), the Turonian Stage begins in the platform with the *Praeactinocamax plenus triangulus* Zone. This taxon of belemnites is rather frequent near the Turonian base in the East European platform (Tuskar' Formation of the Voronezh anteclise, Oktyabr'sk and Bannovo formations of the Khoper monocline, Murom–Lomovka and Ul'yanovsk–Saratov depressions), but its stratigraphic range is imprecisely calibrated with the ammonite standard. According to stratigraphic position, the zone may correspond to the *Watinoceras devonense* Zone of the ammonite scale.

Mytiloides labiatus–Mytiloides kossmati Zone. In recent years, stratigraphic range of the *Mytiloides labiatus–Mytiloides kossmati* Zone that is terminal one in the lower Turonian Substage changed considerably. Naidin *et al.* (1984a, 1984b, 1986) regarded the upper part of the lower Turonian (provided that the stage is divided in two subunits) as corresponding to the wider *Mytiloides labiatus–Mytiloides subhercynicus–Mytiloides hercynicus* Zone. As is established at present, the *Mytiloides subhercynicus* and *M. hercynicus* zones correspond to the middle–upper Turonian *Collignoniceras woollgari* Zone of the ammonite standard (Kennedy *et al.*, 2000). Marcinowski *et al.* (1996) correlated the

Table 3. Correlation between principal stratigraphic schemes of Cenomanian–Turonian boundary deposits

General scale and regional stratigraphic subdivisions of the Russian platform (Olfer'ev and Alekseev, 2002)				East European paleobiogeographic province (Naidin, 1986; Atabekyan *et al.*, 1986), Mangyshlak, and eastern circum-Caspian region (Naidin *et al.*, 1984a, 1984b)			Central Poland (Walaszczyk, 1992)			Mangyshlak (Marcinowski *et al.*, 1996)				Colorado, United States (Kennedy *et al.*, 2000)				
Stage	Substage	Zones of general ammonite scale	Inoceramid and belemnite zones of the Russian platform	Stage	Substage	Molluscan zonation	Stage	Substage	Inoceramid zones	Stage	Substage	Ammonite zones	Inoceramid and cephalopod zones	Stage	Substage	Ammonite zones	Inoceramid zones	Stratigraphic ranges of inoceramids
Turonian	middle (partially)	*Kamerunoceras turoniense/Collignoniceras woollgari*	*Mytiloides hercynicus–Mytiloides subhercynicus*	Turonian	lower	*Inoceramus hercynicus–Inoceramus subhercynicus–Inoceramus labiatus*		middle (partially)	*Mytiloides hercynicus*	Turonian	middle (partially)	*Collignoniceras woollgari*	*Mytiloides hercynicus*	Turonian	middle (partially)	*Collignoniceras woollgari*	*Mytiloides subhercynicus*	
	lower	*Mammites nodosoides*	*Mytiloides labiatus – Mytiloides kossmati*				Turonian	lower	*Mytiloides labiatus*		lower	*Mammites nodosoides*	*Mytiloides labiatus Mytiloides kossmati*		lower	*Mammites nodosoides*	*Mytiloides mytiloides*	
		Watinoceras coloradoense				*Praeactinocamax triangulus*			*Mytiloides kossmati*			*Watinoceras coloradoense*				*Vascoceras birchbyi*	*Mytiloides kossmati*	
		Pseudoaspidoceras flexuosum							*Mytiloides hattini*				*Mytiloides hattini*			*Pseudoaspidoceras flexuosum*		
		Watinoceras devonense	*Praeactinocamax plenus triangulus*													*Watinoceras devonense*	*Mytiloides puebloensis*	
Cenomanian	upper	*Nigericeras scotti*	*Mytiloides hattini*													*Nigericeras scotti*	*Mytiloides hattini*	
		Neocardioceras juddii	*Inoceramus pictus bohemicus*	Cenomanian	upper	*Sciponoceras gracile Inoceramus pictus bohemicus Praeactinocamax plenus plenus*				Cenomanian	upper	*Neocardioceras juddii*	*Neocardioceras juddii*			*Neocardioceras juddii*	*Inoceramus pictus*	
		Metoicoceras geslinianum	*Inoceramus pictus pictus/Praeactinocamax plenus longus*									*Metoicoceras geslinianum*	*Praeactinocamax plenus*			*Sciponoceras gracile*		
		Calycoceras guerangeri				*Eucalycoceras pentagonum*						*Calycoceras guerangeri*						

Mytiloides hattini Elder
Mytiloides puebloensis Wal.
Mytiloides kossmati (Heinz.)
Mytiloides mytiloides (Mant.)
Mytiloides labiatus (Schloth.)
Mytiloides subhercynicus (Seitz.)

Mytiloides kossmati and *M. labiatus* zones, which have been distinguished by Walaszczyk (1992) in the terminal lower Turonian, with upper strata of the *Watinoceras coloradoense* Zone coupled with *Mammites nodosoides* Zone of the general ammonite scale. As was established afterward (Kennedy *et al.*, 2000), the base of *Mytiloides kossmati* Zone is situated outside the *Watinoceras coloradoense* Zone and coincides with the base of underlying *Pseudaspidoceras flexuosum* Zone of the ammonite scale. Therefore, the *Mytiloides labiatus–Mytiloides kossmati* Zone of the East European platform is correlative with three upper ammonite zones of the lower Turonian in the general scale. This subdivision is established in Mordovia, Ul'yanovsk and Kuibyshev areas (Glazunova, 1972), in southwestern Lithuania and Belarus, in the southern periphery of the Donetsk basin, and in sections of the L'viv centrocline (Naidin and Morozov, 1986).

The inoceramid zonation established by Walaszczyk (1992) in central Poland and traceable in the Mangyshlak sections (Marcinowski *et al.*, 1996) has been used to determine regional zones of the middle and upper Turonian in our scale.

Mytiloides hercynicus–Mytiloides subhercynicus Zone. In the East European platform, the middle Turonian substage spans a succession of *Mytiloides hercynicus–Mytiloides subhercynicus, Inoceramus apicalis*, and *Inoceramus lamarcki* zones. Kennedy *et al.* (2000) established that the base of *Mytiloides subhercynicus* Zone corresponds in the Pueblo section of the United States to the first occurrence level of ammonite species *Collignoniceras woollgari* (Mant.) whose appearance is suggested to be an indicator of the middle Turonian base (Bengtson, 1996). The ammonite form *Collignoniceras woollgari* (Mant.) also known from Turonian deposits of the Russian plate (Ovechkina *et al.*, 2002) is extremely rare here, whereas zonal index species of inoceramids are more widespread. The latter have been encountered in sections of the L'viv centrocline and in eastern areas of the Dnieper–Donets depression (Naidin and Morozov, 1986).

Inoceramus apicalis Zone. This zone spans the middle interval of the middle Turonian. It has been established with confidence in the Volga River basin (Penza, Ul'yanovsk, and Saratov areas; Glazunova, 1972), where its thickness is insignificant. The zone has been also distinguished in sections of the L'viv centrocline and in the circum-Caspian depression (Naidin and Morozov, 1986) (Sobetskii *et al.*, 1982).

Inoceramus lamarcki Zone. This zone is terminal one in the middle Turonian Substage. Corresponding deposits are widespread and readily recognizable almost everywhere in the East European platform. Inoceramids characteristic of the zone, the index species included, have been listed by description of Turonian deposits in a series of explanatory notes to edited medium-scale geological maps.

Inoceramus costellatus Zone has been established in Germany (Ernst *et al.*, 1963), Poland (Walaszczyk, 1992), and western Kazakhstan (Marcinowski *et al.*, 1996). Its presence in the Russian plate has not been substantiated yet by paleontological data. In the East European paleobiogeographic province, Naidin *et al.* (1986) recognized the wider *Inoceramus costellatus–Inoceramus striatoconcentricus* Zone of the terminal Turonian interval.

Mytiloides striatoconcentricus Zone. In the East European platform, this subdivision is traceable in the Volgograd area and Ilovlya River basin (Glazunova, 1972), and also in the Saratov area and circum-Caspian depression (Sobetskii *et al.*, 1982).

Mytiloides scupini–Mytiloides incertus Zone crowns the upper Turonian. It is established in the Salzgitter-Salder section near Hannover in Germany above the *Mytiloides striatoconcentricus* Zone (Walaszczyk and Tröger, 1996; Kauffman *et al.*, 1996). The lower boundary of the Coniacian Stage is defined in the same section at the top of zone under consideration (Kauffman *et al.*, 1996). The *Mytiloides scupini–Mytiloides incertus* Zone has not been recognized yet in the Russian plate, but its presence is proved in adjacent western and eastern regions (Kauffman *et al.*, 1996; Walaszczyk, 1996; Marcinowski *et al.*, 1996; Walaszczyk, Wood, 1998).

Coniacian Stage. Like in the case of Turonian deposits, we used the inoceramid zonation to outline biostratigraphy of the Coniacian Stage in the Russian plate. In distinction from the scheme suggested by Naidin *et al.* (1986), we managed to considerably detail the stage zonation, using new data from a series of works (Walaszczyk, 1992; Marcinowski *et al.*, 1996; Kauffman *et al.*, 1996; Walaszczyk and Wood, 1998), and to verify stratigraphic range of the stage. According to the former concept, the Coniacian Stage base coincided "with the base of the *Inoceramus schloenbachi* (=*Inoceramus deformis*) Zone" (Naidin *et al.*, 1986, p. 15). Recent data (Kauffman *et al.*, 1994, 1996) showed, however, that biozone of aforementioned species corresponds in the North American Interior basin to the lower part of the *Volviceramus koeneni* Zone, thus being located at the base of the middle Coniacian Substage.

As the International Working Group recommended to authorize the first occurrence level of bivalve mollusk *Cremnoceramus rotundatus* (sensu Tröger) for the lower boundary of the Coniacian Stage, we discriminated near the stage base the synonymous zone that was originally distinguished in Germany (Ernst *et al.*, 1983; Wood *et al.*, 1984).

The *Cremnoceramus rotundatus* Zone has been established in the Salzgitter-Salder section (Kauffman *et al.*, 1996). In the East European platform, it is known in the Bryansk area of the Desna River basin and further eastward in the Mangyshlak (Marcinowski *et al.*, 1996). Recent reexamination of classical Coniacian

sequences in the Lower Saxony, central Poland, and the Western Interior basin (Walaszczyk, Wood, 1998; Walaszczyk, Cobban, 2000) showed that the species *Cremnoceramus rotundatus* (sensu Tröger non Fiege) is a junior synonym of North American *Cremnoceramus erectus* (Meek). Accordingly, it was suggested to regard this taxon as a subspecies of the *Cremnoceramus deformis* (Meek) phylogenetic lineage and to rename the *Cremnoceramus rotundatus* Zone as the *Cremnoceramus deformis erectus* Zone.

The *Cremnoceramus brongniarti* Zone established by Walaszczyk (Walaszczyk, 1992; Marcinowski *et al.*, 1996) approximately corresponds in range to the former *Cremnoceramus erectus* Zone (Ernst *et al.*, 1983; Wood *et al.*, 1984). According to recent data (Walaszczyk and Wood, 1998), it can be divided into the *Cremnoceramus waltersdorfensis hannovrensis* and *Cremnoceramus inconstans* zones. The unit under consideration has been recognized in the Desna River basin, southern Donetsk basin (Kotsyubinskii *et al.*, 1974), and Ural–Emba region (Marcinowski *et al.*, 1996).

The *Cremnoceramus crassus–Cremnoceramus deformis* Zone is terminal one in the lower Coniacian Substage. It is known in sections of the L'viv centrocline, southern Donetsk basin, and also in the west of the Voronezh anteclise, in the east of the Dnieper–Donets depression (Naidin and Morozov, 1986), and in the Mangyshlak (Marcinowski *et al.*, 1996). In opinion of Walaszczyk and Cobban (2000), the zone is an equivalent of the *Cremnoceramus crassus crassus* Zone of the terminal lower Coniacian in the United States. Walaszczyk (2000) also assumed that *Cremnoceramus* Beds do not crown the lower Coniacian Substage. After revision of fossils collected by Olfer'ev in the Bryansk area, Walaszczyk concluded that the terminal lower Coniacian subdivision corresponds to the *Inoceramus gibbosus* Zone.

After recommendations of the International Working Group, the lower–middle Coniacian boundary is defined at the appearance level of inoceramid form *Volviceramus koeneni* (Möll.) representing the index species of lower zone in the middle Coniacian Substage. The last zone completely corresponds in range to the *Peroniceras tridorsatum* Zone of the general ammonite scale (Kauffman *et al.*, 1994, 1996).

The *Volviceramus koeneni* Zone is recognizable above the appearance level of its index species and subspecies *Cremnoceramus schloenbachi schloenbachi* (Böhm) (Kauffman *et al.*, 1994). In the Russian plate, this zone is known only the L'viv centrocline (Naidin and Morozov, 1986).

The *Volviceramus involutus* Zone was widely acknowledged some time ago under the name "*Inoceramus involutus* Zone," because this index species with distinctive morphological features is easily recognizable. This subdivision was regarded formerly as corresponding in stratigraphic range either to the entire Coniacian Stage, or to its upper half, if the stage is divided in two substages (Table 1). With its new, much narrower range approximately corresponding to the *Cremnoceramus wandereri* (Andert) Biozone (Kauffman *et al.*, 1994), the zone crowns the Coniacian Stage and can be traced in many areas of the East European platform. Hardenbol *et al.* (1998) correlated this subdivision with the *Gauthiericeras margae* Zone of the ammonite scale.

Magadiceramus subquadratus Zone. In accord with the same recommendations of the International Working Group (Kauffman *et al.*, 1996), the middle–upper Coniacian boundary is defined at the first occurrence level of inoceramid forms *Magadiceramus subquadratus* (Schlüter) representing index species of the indicated zone. In two well-known stratigraphic schemes (Marcinowski *et al.*, 1996; Hardenbol *et al.*, 1998), the *Magadiceramus subquadratus* Zone is correlated with the upper Coniacian *Paratexanites serratomarginatus* Zone of the ammonite scale. In the Russian plate, the zone under consideration has been established in western Ukraine and in the Bryansk area.

Santonian Stage. The International Working Group on Santonian Stage recommended to accept the first occurrence level of inoceramid form *Cladoceramus undulatoplicatus* (Roem.) for the Coniacian–Santonian boundary. This form is however unknown in the East European platform, where we have instead the abundant inoceramids of *cardissoides* group, such as *Sphenoceramus pachti* (Arkh.) and *S. cardissoides* (Goldf.), which are, in opinion of Arkhangel'skii (1912, 1922), indicators of the Santonian base. As we already mentioned considering general biozonation of the Santonian Stage (Olfer'ev and Alekseev, 2002), the coincidence of basal levels of the *Cladoceramus undulatoplicatus* and *Sphenoceramus cardissoides* zones is doubtful. Recent investigations in northwestern Germany (Kaplan and Kennedy, 2000) and Austria (Lamolda and Hancock, 1996) showed that *cardissoides* forms appear earlier than *Cladoceramus undulatoplicatus* (Roemer). The inversed order of occurrence levels is recorded, however, in southern England (Bailey *et al.*, 1983) and in France, on the opposite side of the English Channel (Amedro and Robaszynski, 2000), and Naidin noted the same situation in western Kazakhstan (*Stratigraficheskie...*, 1996). In the Western Interior basin of North America (Kauffman *et al.*, 1994) and also in the Boreal province (Dhondt, 1992; Lopez *et al.*, 1992), Caucasus and Central Asia (Atabekyan, 1986; Moskvin, 1986), both taxa have concurrent ranges.

Sphenoceramus cardissoides–Texanites texanus–Belemnitella propinqua propinqua Zone. Following Arkhangel'skii (1912), Naidin (*Stratigraficheskie...*, 1996), Hardenbol *et al.* (1998), Tröger and Summesberger (1994), Walaszczyk (1992), and Marcinowski *et al.* (1996), we discriminate a basal Santonian interval that yields *Sphenoceramus cardissoides* (Goldf.). Other

characteristic taxa occurring in this interval are *Texanites texanus* (Roemer) known from the Terepsha Formation of the Voronezh anteclise and more widespread *Belemnitella propinqua propinqua* (Mob.) (Naidin and Kopaevich, 1977; Christensen, 1990). Exactly this triad of fossils defines stratigraphic range of the lower Santonian Substage in the East European platform.

Sphenoceramus patootensis–Belemnitella preacursor praepraecursor Zone. Naidin *et al.* (1986) regarded the complex *Sphenoceramus patootensis–Gonioteuthis granulata* Zone as an equivalent of the upper Santonian. We accept the first taxon for the index species of the substage, although the concurrent interval in inoceramid zonations (Tröger, 1989; Walaszczyk, 1992) is termed as the *Sphenoceramus patootensiformis* Zone or the unit 29 in nomenclature of Tröger. The fact is that the last form has stratigraphic range spanning the coupled upper Santonian and lower Campanian interval and is therefore inappropriate index species for the upper Santonian proper.

As for the second index species included by Naidin and his colleagues in the complex zone name, it seems to be inappropriate as well. Belemnites of the genus *Gonioteuthis* are characteristic of southern areas of the Central European subprovince distinguished by Christensen (1990), being extremely rare in northern areas of the Russian plate, where they have been found in single sections located on the southern slope of the Voronezh anteclise. Findings of subspecies *Gonioteuthis granulata granulata* (Blainv.) are unknown so far from the study region of the Central Russian subprovince, where the Santonian–Campanian sequences yield instead the abundant representatives of the genus Belemnitella. According to Naidin (1964), subspecies *Belemnitella praecursor praepraecursor* Najd. is most characteristic of the upper Santonian, and we used it to designate the second index taxon of the corresponding zone.

Campanian Stage. Belemnitella praecursor mucronatiformis Zone. Naidin *et al.* (1986) who distinguished the *Actinocamax laevigatus–Belemnitella praecursor mucronatiformis* Zone of the East European paleobiogeographic province as the lower one in the Campanian Stage regarded it as a stratigraphic equivalent of the *Gonioteuthis granulataquadrata–Placenticeras bidorsatum* Zone in Germany (Naidin, 1979). In the name of this belemnite zone, we left only the last taxon, because *Actinocamax laevigatus* Arkh. is widespread, as established now, not only in the so-called "*Pteria* Beds" of a disputable Campanian age, but also in the underlying upper Santonian deposits of the Voronezh anteclise, their basal strata included. We do not exclude as well that the zone under discussion includes the topmost portion of the upper Santonian (*marsupites* Beds).

Belemnitella mucronata alpha Zone. Naidin *et al.* (1986) attributed to this zone the beds with *Gonioteuthis quadrata quadrata* Blainv. and *Belemnitella mucronata alpha* Schatsky. In the zone name, we retain only the second taxon, because the first one is extremely rare and has been established in the *Pteria* Beds of the Boguchar and Belaya Gorka localities (Naidin *et al.*, 1980, p. 34), where they belong to underlying zones of the lower Campanian and upper Santonian that is incompatible with the currently authorized stratigraphic range of *Gonioteuthis quadrata quadrata* Blainv.

Belemnellocamax mammillatus Zone. Because of the same reasons, we excluded subspecies *Gonioteuthis quadrata gracilis* (Stoll.) from the former name of the terminal lower Campanian zone and left only the index species *Belemnellocamax mammillatus* (Nilss.) whose subspecies *B. mammillatus mammillatus* (Nilss.) and especially *B. mammillatus volgensis* Najd. are widespread in eastern areas of the Russian plate. Subspecies *Gonioteuthis quadrata gracilis* (Stoll.) typical of the uppermost lower Campanian in northwestern Europe (Christensen, 1990) is known in the study region from the *Pteria* beds of the Boguchar and Belaya Gorka sections (Naidin *et al.*, 1980), i.e., from the lower level of the *Belemnitella praecursor mucronatiformis* Zone.

Hoplitoplacenticeras coesfeldiense–Belemnitella mucronata mucronata Zone. For the lower zone of the upper Campanian, we accepted the name *Hoplitoplacenticeras coesfeldiense–Belemnitella mucronata mucronata* Zone suggested by Naidin *et al.* (1986), although these ammonite taxa were formerly detected only southward of the study region, in the L'viv centrocline, southern Donetsk basin, and western Kazakhstan (Naidin and Morozov, 1986; *Stratigraficheskie skhemy,* 1996). Recently, V.B. Sel'tser discovered the ammonite assemblage of *Hoplitoplacenticeras coesfeldiense coesfeldiense* (Schlöt.), *H. coesfeldiense costulosum* (Schlöt.), *H.* cf. *vari* (Schlöt.), and *Trachyscaphites gibbus* (Schlöt.) in the Mezino-Lapshinovka section located to the northwest of Saratov. Belemnite rostra of *Belemnitella mucronata mucronata* (Schlöt.) are known from the basal upper Campanian almost everywhere in the Russian plate. The indicated zone corresponds to the lower zone of the general upper Campanian ammonite zonation.

The *Belemnitella langei* Zone originally distinguished by Naidin *et al.* (1986) represents the overlying zone of the upper Campanian Substage. Its deposits are widespread in the Voronezh anteclise and Volga River basin. The unit base is defined at the first occurrence level of its index species. According to changes in phylogenetic lineage of the late Campanian *Belemnitella langei* Schatsky, Naidin distinguished the succession (from the base upward) of *Belemnitella langei minor, Belemnitella langei langei,* and *Belemnitella langei najdini* subzones. It was also stated that "stratigraphic ranges of subzones represent epiboles of corresponding subspecies" (Naidin and Kopaevich, 1977, p. 98).

Characteristic late Campanian ammonite taxa included in the nomenclature of above subzones enable correlation between these and concurrent West Euro-

pean biostratigraphic subdivisions. In general, the upper Campanian *Belemnitella langei* Zone of the Russian plate is subdivided (from the base upward) into the *Belemnitella langei minor–Bostrychoceras polyplocum, Belemnitella langei langei–Didymoceras donezianum,* and *Belemnitella langei najdini–Micraster grimmensis* subzones. The last index species represents the echinoderm assemblage of the Vol'sk section.

The *Belemnitella langei najdini–Micraster grimmensis* Subzone yields foraminifers of the *Brotzenella taylorensis* Zone (*Prakticheskoe...*, 1991) that is correlative with the *Osangularia navarroana* Zone of northwestern Germany. Consequently, the aforementioned regional subdivision of macrofauna corresponds to the lower part of the upper Campanian *Micraster grimmensis* Zone in that country (Schönfeld and Burnett, 1991; Christensen, 1993; Beniamovskii and Kopaevich, 1998).

The *Belemnella licharewi–Micraster grimmensis* Zone is terminal one in the upper Campanian Substage. Jeletzky (1948) originally attributed the *Belemnella licharewi* Zone to the basal lower Maastrichtian, but he denied his initial opinion later on (Jeletzky, 1958). Nevertheless, the Maastrichtian age of *licharewi* Beds was argued for since the 1950s in a series of works (Naidin, 1960, 1996; Naidin *et al.*, 1984a,1984b, 1986; Kopaevich *et al.*, 1987). According to additional data, the *Belemnella licharewi* Zone bears foraminifers of the *Angulogavelinella gracilis* Zone (Kopaevich *et al.*, 1987) that is an analogue of the West European *Bolivinoides peterssoni* Zone (Beniamovskii and Kopaevich, 1998). Consequently, the *Belemnella licharewi* Zone should be correlated with the upper part of the *Micraster grimmensis* Zone of Germany (Schönfeld and Burnett, 1991). With due account for all these data, we discriminated the described zone under the double name in our scheme.

Maastrichtian Stage. Acanthoscaphites tridens Zone. The regional scale of the Upper Cretaceous of the East European platform includes two zones attributed to the Maastrichtian Stage, which correspond, according to Naidin (1978), to the *Hoploscaphites constrictus* (J. Sow.) Biozone. The lower *Acanthoscaphites tridens* Zone is divided into the lower *Belemnella lanceolate* and upper *Belemnella sumensis* subzones. The base of the former coincides with the base of synonymous belemnite zone of northwestern Europe and Balto-Scandia (Christensen, 1990). Simultaneously, it approximately corresponds to the lower boundary of the ammonoid *Pseudokossmaticeras tersense* Zone and lies inside the subzone CC23a of the nannoplankton scale (Hancock *et al.*, 1993).

The *Belemnella sumensis* Subzone is an equivalent of the West European *Belemnella occidentalis* Zone (Kopaevich *et al.*, 1987). Its base is situated in the upper portion of the nannoplankton subzone CC23b (Schönfeld and Burnett, 1991; Jagt and Felder, 1999), thus being approximately at the level of lower boundary of the *Pachydiscus epiplectus* Zone of the general ammonite scale (Hancock *et al.*, 1993).

The *Belemnitella junior–Neobelemnella kazimiroviensis* Zone terminates the Maastrichtian Stage of the Russian plate and corresponds to synonymous zone in the stage stratotype (Jagt, 1999). It is not easy to divide this zone in two parts, as it is evident from a thorough stratigraphic analysis by Kopaevich *et al.* (1987). The zone base approximately corresponds to the lower boundary of the nannoplankton zone NC22 or subzone CC25b (McLaughlin *et al.*, 1995) and to the base of *Anapachydiscus fresvillensis* Zone in the ammonite scale, which is believed to be the boundary between the lower and upper Maastrichtian.

ZONATION OF BENTHIC FORAMINIFERS

Benthic foraminifers are widely used in practice of subdivision of Upper Cretaceous deposits in the East European platform. Scientists who contributed much to development of the regional foraminiferal scale are V.S. Akimets, V.T. Balakhmatova, V.I. Baryshnikova, V.P. Vasilenko, A.M. Voloshina, A.A. Grigyalis, L.G. Dain, E.L. Lipnik, and E.V. Myatlyuk. The first zonal scheme for Upper Cretaceous benthic foraminifers from the Russian plate has been suggested by Grigyalis *et al.*, (1974, 1980). In fact, it was a modification of scheme elaborated by Vasilenko (1961) for the Mangyshlak. In recent years, the scheme was considerably refined by Kopaevich and Beniamovskii. The regional zonation of benthic foraminifers presented in this work was approved at the workshops in Kiev (1988) and Kamenets-Podol'skii (1989). With minor corrections, it was included afterward in "Practical Guide to Microfauna of the USSR, vol. 5: Mesozoic Foraminifers" published in 1991. In 2000, Bureau of the Regional Interdepartmental Stratigraphic Commission on Central and Southern Russian Platform organized a special Working Group that somewhat amended the scheme. We took account of these corrections in our scheme though with some modifications, bearing in mind new data on distribution ranges of index species, which have been obtained in the last two years of comprehensive study on the Upper Cretaceous biostratigraphy in the Russian plate.

Cenomanian Stage. The lower *Gavelinella cenomanica* Zone of the stage that has been originally distinguished by Vasilenko (1961) corresponds to the *Schloenbachia varians–Turrilites costatus* Zone of macrofauna. In addition to index species, its foraminiferal assemblage includes *Hagenowella chapmani* (Cushm.), *Tritaxia cenomana* Gorb., *Arenobulimina conoidea* (Pern.), *Eggerellina cenomana* Akim., *Marssonella gomelina* Akim., *Marginulina jonesi* (Reuss), *Gavelinella baltica* Brotz., *G. mirtchinki* (Akim.), *G. minutissima* (Akim.), *Lingulogavelinella formosa* (Brotz.), *L. orbiculata* (Kusn.), *L. ornatissima* (Lipn.), *Cibicidoides gorbenkoi* (Akim.), and *Guembelitria*

cenomana (Kell.). The appearance level of these benthic foraminifers defines the base of subdivision.

The *Lingulogavelinella globosa* Zone of the upper Cenomanian has been distinguished by Akimets (1970). Its lower boundary corresponds to the appearance level of index species *Lingulogavelinella globosa* (Brotz.) in association with *Spiroplectammina cuneata* Vass., *Gaudryina arenosa* Akim., *G. angustata angustata* Akim., *G. folium* Akim., *Gyroidinoides conica* (Vass.), *G. nitidus* (Reuss), *Gavelinella vesca* (N. Byk.), *G. loevi* (Akim.), *Brotzenella belorussica* (Akim.), *B. berthelini* (Kell.), *Cibicides polyrraphes polyrraphes* (Reuss), *C. minusculus* Akim., and *Bolivina spectabilis* (Akim.). Concurrent planktonic foraminifers are represented by *Hedbergella caspia* (Vass.), *H. delrioensis* (Carsey), *Whiteinella archeocretacea* (Pess.), *W. brittonensis* (Loebl. et Tapp.), and *W. paradubia* (Sigal.). This zone spans the middle and upper Cenomanian substages, except for the *Turrlites costatus* Subzone of the general scale.

Turonian Stage. The *Gavelinella nana* Zone was distinguished by Akimets *et al.*, (1991) at the appearance level of benthic foraminifers *Arenobulimina presli* (Reuss), *Globorotalites hangensis* Vass., *G. turonicus* Kaev., *Eponides turonicus* Lipn., *Gavelinella nana* (Akim.), *G. ammonoides* (Reuss), *G. kelleri dorsoconvexa* Akim., and *Reussella turonica* Akim. It is correlated with three lower Turonian zones of molluscan fauna (*Praeactinocamax plenus triangulus, Mytiloides labiatus–Mytiloides kossmati*, and *Mytiloides hercynicus–Mytiloides subhercynicus*). Northward of Moscow, the aforementioned assemblage is known from the Chernevo Formation that yields ammonite species *Collignoniceras woollgari* (Mant.) identified by Atabekyan and nannoplankton characteristic of the zone CC11 (Ovechkina *et al.*, 2002). In the southeast of the East European platform (Bragina *et al.*, 1999), larger forms of *Hedbergella* group, such as *Hedbergella holzli* (Hagn et Zeil.), *Whiteinella paradubia* (Sigal), and *W. bornholmensis* (Dougl.) prevail among foraminifers of the zone.

The *Gavelinella moniliformis* Zone has been originally established by Akimets (1974) as corresponding to that part of the upper Turonian of the Russian plate, which begins with the molluscan *Inoceramus apicalis* Zone. The index species first appearing in the unit is associated with *Spiroplectammina praelonga* (Reuss), *Verneuilina muensteri* Reuss, *Gaudryina laevigata* Franke, *G. variabilis* Mjatl., *Arenobulimina minima* Vass., *Globorotalites multiseptus* Brotz., *Stensioeina praeexsculpta* Kell., *S. laevigata* Akim., *Eponides concinnus* Brotz., *Osangularia whitei praeceps* (Brotz.), *Gavelinella ammonoides* (Reuss), *Reussella carinata* Vass., and *R. kelleri* Vass. *Gavelinella praeinfrasantonica* (Mjatl.) and *Ataxophragmium nautiloids* Brotz. appear in terminal strata of the zone. The listed benthic taxa may occur in association with keeled planktonic foraminifers *Marginotruncana lapparenti* (Brotz.), *M. marginata* (Reuss), *M. pseudolinneiana* Pess., and *M. renzi* (Gand.). The indicated stratigraphic interval yields nannoplankton of the zone CC12.

Coniacian Stage. The *Gavelinella kelleri* Zone in original nomenclature of Grigyalis *et al.*, (1974) corresponds to epiboles of species *Ataxophragmium nautiloids* Brotz., *Gavelinella kelleri* Mjatl., and *G. praeinfrasantonica* Mjatl. Characteristic of this zone are first appearing *Gaudryina coniacica* Akim., *Ataxophragmium compactum* Brotz., *Valvulineria praebiconvexa* Lipn., *Stensioeina emscherica* Baryshn. [the known in Russia is subspecies *S. granulata granulata* (Orb.)], *Eponides biconvexus* Marie, *Gavelinella giedroyci* Grig., and *Cibicidoides praeeriksdalensis* (Vass.). Other taxa typical of the zone are *Heterostomella carinata* (Franke), *Marssonella oxycone* Reuss, *Globorotalites multiseptus* Brotz., *Osangularia whitei whitei* (Brotz.), and *Gavelinella moniliformis* (Reuss). Rather abundant *Hedbergella agalarovae* (Vass.), *Whiteinella brittonensis* (Loeb. et Tapp.), *Marginotruncana marginata* (Reuss), *M. renzi* (Gand.), *M. coronata* (Bolli), and *Heterohelix moremani* (Cushm.) represent planktonic foraminifers of the unit. The assemblage under consideration also includes *Spiroplectammina praelonga* (Reuss), *Stensioeina praeexsculpta praeexsculpta Kell., Gavelinella ammonoides (Reuss), and Cibicides polyrraphes polyrraphes* (Reuss), which disappear in the overlying zone. The *Gavelinella kelleri* Zone is correlative with three lower inoceramid zones of the Coniacian Stage and correspond to the lower substage of the latter. The concurrent nannoplankton characteristic of zone CC13 suggests the same stratigraphic level.

The *Gavelinella thalmanni* Zone has been adopted at the workshop aimed to elaborate the Upper Cretaceous foraminiferal scale for the East European platform and held in Kamenets-Podol'skii (1989). The zone is named after the index species *Gavelinella thalmanni* (Brotz.) in distinction from the former *Gavelinella costulata* Zone accepted in the Practical Guide to Microfauna of the USSR (*Prakticheskoe...*, 1991). The last name appears to be inappropriate because of two reasons. First, species *Gavelinella costulata* described by Myatlyuk considerably differs from *Gavelinella costulata* (Marie) described much earlier (Marie, 1941) as a form appearing in the Campanian Stage. As a result, one can meet in publications two synonymous taxa—*Gavelinella costulata* (Mjatl. non Marie) and *G. costulata* (Marie non Mjatl.), stratigraphic ranges of which are different. Second, *Gavelinella costulata* (Mjatl. non Marie) appears, in distinction from *Gavelinella thalmanni* (Brotz.), already in the lower *Gavelinella kelleri* Zone. Characteristic benthic foraminifers appearing in the *Gavelinella thalmanni* Zone in association with its index species are *Spiroplectammina embaensis* Mjatl., *Gavelinella infrasantonica* (Balakhm.) [*G. vombensis* (Brotz.) in nomenclature of West European paleontologists], *Cibicidoides eriksdalensis* (Brotz.), and *Bolivinitella eleyi*

(Cushm.). *Gaudryina laevigata* Franke, *Ataxophragmium compactum* Brotz., *Stensioeina emscherica* Baryschn., "*Gavelinella costulata* (Mjatl.)," *Cibicidoides praeeriksdalensis* (Vass.), and *Reussella kelleri* Vass. continue their existence at this level, while evolution of *Gavelinella kelleri* (Mjatl.) and *Gavelinella moniliformis* (Reuss) is terminated here. The zone under consideration corresponds to three upper inoceramid zones of the Coniacian Stage, i.e., to the middle and upper substages of the latter. Coexisting nannoplankton of zone CC14 is another evidence in favor of this conclusion.

Santonian Stage. The *Gavelinella infrasantonica* Zone Vasilenko (1961) who originally distinguished this zone used a lame index species to term the unit despite the mass abundance of *Gavelinella infrasantonica* (Balakhm.) in the corresponding interval, because this form is known in the East European platform and northwestern Germany (Schönfeld, 1990) beginning from the middle Coniacian Substage. Other diagnostic taxa of the zone are the appearing here *Spiroplectammina rosula* (Ehr.), *Arenobulimina courta* (Marie), *Martinottiella communis* (Orb.), *Ataxophragmium crassum* (Orb.), *Neoflabellina rugosa* (Orb.), *Valvulineria laevis* Brotz., *V. marie* Vass., *Stensioeina exsculpta exsculpta* (Reuss), *Eponides concinnus planus* Vass., *Osangularia whitei crassa* Vass., *O. w. polycamerata* Vass., *Cibicides ribbingi* Brotz., *Praebulimina ventricosa* (Brotz.), and *Cuneus buliminoides* (Brotz.). The zonal foraminiferal assemblage also includes *Gaudryina laevigata* Franke, *Globorotalites multiseptus* Brotz., *Osangularia whitei whitei* (Brotz.), *Cibicides excavatus* Brotz., *Cibicidoides eriksdalensis* (Brotz.), and *Bolivinitella eleyi* (Cushm.), all known from underlying strata as well. Taxa terminating their evolution in the zone are *Spiroplectammina embaensis* Mjatl., *Arenobulimina orbignyi* (Reuss), *Gavelinella costulata* (Mjatl. non Marie), *G. giedroyci* Grig., and *G. thalmanni* (Brotz.). The *Gavelinella infrasantonica* Zone is identical in range to the *Texanites texanus–Sphenoceramus cardissoides–Belemnitella propinqua propinqua* Zone of molluscan fauna.

The *Gavelinella stelligera* Zone is included in our scale in the range suggested by Akimets *et al.*, (1979). This upper zone of the Santonian Stage reveals predominance of first appearing species *Gaudryina rugosa* Orb., *Arenobulimina senonica* Mjatl., *Ataxophragmium orbignynaeformis* Mjatl., *Orbignyina variabilis* (Orb.), *Stensioeina granulata incondite* Koch, *S. granulata perfecta* Koch, *S. mursataiensis* Vass., *Gavelinella stelligera* (Marie), *G. santonica* Akim., and *Sitella carseyae* (Plumm.). This assemblage is well correlative with those characterizing the terminal middle (beginning from the *Stensioeina granulata incondite* Zone after Schönfeld, 1990) and upper Santonian of northwestern Germany (Table 4).

Foraminifers from the upper part of *Gavelinella stelligera* Zone represent an assemblage transitional in composition to the Campanian one. All characteristic taxa listed above coexist at this level with newcomers *Heterostomella praefoveolata* Mjatl., *Arenobulimina vialovi* Wolosch., *A. obliqua* (Orb.), *Egerrellina brevis* (Orb.), *E. ovoidea* Marie, *Orbignyina convexocamerata* Wolosch., *O. inflata* (Reuss), *O. irreperta* Wolosch., *Voloschinovella aequisgranensis* (Beis.), *Valvulineria biconvexa* Lipn., *Stensioeina pommerana* Brotz., *Eponides* aff. *grodnoensis* Akim., *Osangularia cordieriana* (Orb.), *Gavelinella bistellata* (Gorb.), *G. dainae* (Mjatl.), *G. costulata* (Marie), *Brotzenella insignis* (Lipn.), *Pullenia dampelae* Dain, *Cuneus triangulus* (Cushm. et Park.), *Bolivina funalis* Wolosch., and *Bolivinoides strigillatus* (Chapm.). Concurrent planktonic forms are *Rugoglobigerina ordinata* (Subb.) and *R. kelleri* (Subb.). Owing to abundance of *Stensioeina pommerana* (Brotz.) and absence of *Gavelinella clementiana clementiana* (Orb.), we defined the interval of indicated assemblage as the *Stensioeina pommerana* Beds, which are correlative with the synonymous subzone of the European paleobiogeographic province (Beniamovskii and Kopaevich, 1998) or with the *Stensioeina pommerana–Eponides frankei* Zone of northwestern Germany (Schönfeld, 1990). The last subdivision corresponds to the upper *marsupites* Beds of the terminal Santonian in Germany. In areas framing the Donetsk basin on the north, the distribution interval of the assemblage under consideration was defined as the *Gavelinella dainae–Orbignyina inflata* Beds of the lower Campanian (Naidin *et al.*, 1980), which were erroneously placed above the *Gavelinella clementiana clementiana* Beds. Correlation between various zonal schemes of the Santonian Stage in the European paleobiogeographic province is illustrated in Table 4. The *Gavelinella stelligera* Zone of benthic foraminifers corresponds to the *Sphenoceramus patootensis–Belemnitella praecursor praepraecursor* Zone of molluscan fauna.

Campanian Stage. The *Gavelinella clementiana clemetiana* Zone distinguished by Akimets (1980) can be established by appearance of its index species and is traceable throughout the territory of the European paleobiogeographic province, although its deposits are preserved after erosion in a limited number of localities. It corresponds to the molluscan *Belemnitella praecursor mucronatiformis* Zone of the East European platform, and its assemblage is also known from the lower Campanian *Placenticeras bidorsatum* Zone of Germany.

The *Cibicidoides temirensis* Zone was established for the first time by Vasilenko (1961). This upper zone of the lower Campanian is divided in two subzones. The lower *Cibicidoides temirensis* Subzone corresponds to the interval, where its index species show mass abundance. Index species of the upper *Cibicidoides aktulagayensis* Zone coexist with concurrently appearing *Neoflabellina rugosa leptodisca* (Wedek.), *Gavelinella clementiana laevigata* Marie, *Cibicidoides beaumontianus* (Orb.), *Bolivinoides decoratus* (Jones), and *B. laevigatus* Marie. These subzones are equiva-

Table 4. Correlated Santonian zonations of benthic foraminifers in the European paleobiogeographic province (EPP)

Zonation of benthic foraminifers suggested in this work			Western Kazakhstan (Akimets *et al.*, 1991)			Zonation of benthic foraminifers in the EPP (Beniamovskii and Kopaevich, 1998)				Northwestern Germany				Southern England (Baily *et al.*, 1983)	
												(Schönfeld, 1990)	(Koch, 1977)		
Campanian	lower (partially)	*Cibicidoides temirensis*	Campanian	lower (partially)	*Cibicidoides temirensis*	Campanian	lower (partially)	*Bolivinoides decoratus decoratus*	*Cibicidoides temirensis/Gavelinella clementiana usakensis*	Campanian	lower (partially)	*Bolivinoides granulatus*	*Bolivinoides decoratus decoratus*	*Bolivinoides culverensis*	*Pullenia quaternaria*
					Bolivinoides decoratus decoratus				*Bolivinoides decoratus*			*Neoflabellina wedekindi*			*Eouvigerina galeata*
		Gavelinella clementiana clementiana			*Gavelinella clementiana clementiana*			*Gavelinella clementiana clementiana*				*Gavelinella clementiana*			*Gavelinella usakensis*
												Eponides concinna			*Gavelinella cristata*
Santonian	upper	*Gavelinella stelligera* *Stensioeina pommerana* Beds	Santonian	upper	Gavelinella stelligera / Bolivinoides strigillatus	Santonian	upper	*Bolivinoides strigillatus*	*Stensioeina pommerana*	Santonian	upper	*Stensioeina pommerana/Eponides frankei*	*Bolivinoides strigillatus*	*Bolivinoides strigillatus*	*Gavelinella cristata/Globigerinelloides rowei*
					Osangularia				*Gavelinella stelligera*			*Bolivinoides strigillatus*			
				lower	*Stensioeina granulata perfecta*			*Stensioeina granulata perfecta*				*Stensioeina granulata perfecta*	*Stensioeina granulata perfecta*	*Stensioeina granulata perfecta*	
	lower	*Gavelinella infrasantonica*									middle	*Stensioeina granulata incondita*	*Stensioeina granulata polonica*	*Stensioeina granulata polonica*	*Cibicides ex gr. beaumontianus*
												Gaudryina jonesiana			
											lower	*Cicicidoides eriksdalensis/Gavelinella vombensis (=infrasantonica)*			*Loxostomum eleyi*
Coniacian	middle–upper	*Gavelinella thalmanni*			*Stensioeina exsculpta exsculpta*					Coniacian	middle–upper		*Stensioeina exsculpta exsculpta*	*Stensioeina exsculpta exsculpta*	
	lower	*Gavelinella kelleri*	Coniacian	upper	*Stensioeina granulata granulata*						lower	*Praebulimina evolutum*	*Stensioeina granulata granulata*		

lents of two upper subzones of the *Bolivinoides decoratus decoratus* Zone that has been originally established in western Germany (Koch, 1977) and is recognizable in the European paleobiogeographic province (Beniamovskii and Kopaevich, 1998). It is impossible to trace in the Russian plate the lower *Bolivinoides decoratus decoratus* Subzone s. str. (*Prakticheskoe...*, 1991) or *Bolivinoides decoratus decoratus–Bolivinoides granulatus* Subzone (Beniamovskii and Kopaevich, 1998) originally recognized in western Kazakhstan (Naidin *et al.*, 1984; *Prakticheskoe...*, 1991; *Stratigraficheskie...*, 1996). This situation can be explained either by a cryptic hiatus, or by ecological factors, which controlled provincialism of faunal assemblages. The *Cibicidoides temirensis* Subzone corresponds to the *Belemnitella mucronata alpha* Zone of cephalopods, whereas the *Cibicidoides aktulagayensis* Subzone is correlative with the *Belemnellocamax mammillatus* Zone.

Brotzenella monterelensis Zone. The upper Campanian Substage is divided into three zones of benthic foraminifers. The lower *Brotzenella monterelensis* was initially established by Dolitskaya (1961) in the interval, where its index species appears in association with *Arenobulimina puschi* (Reuss), *Orbignyina simplex* (Reuss), *Eponides grodnoensis* Akim., *Brotzenella menneri* (Kell.), *Cibicidoides voltzianus* (Orb.), *Sitella laevis* (Beiss.), *Eouvigerina campanica* Dain, and *Pseudouvigerina cretacea* Cushm. Taxa terminating their evolution in that interval are *Spiroplectammina lingua* Akim., *Brotzenella insignis* Lipn., and *Praebulimina ventricosa* (Brotz.). In its stratigraphic range, the *Brotzenella monterelensis* Zone corresponds to the *Hoplitoplacenticeras coesfeldiense–Belemnitella mucronata mucronata* of cephalopods and to the lower ammonite zone of the upper Campanian in the general scale.

The *Globorotalites emdyensis* Zone was recognized by Akimets (1974) and named after the index species described by Vasilenko in 1961 that is indistinguishable from simultaneously described *Globorotalites hiltermanni* Kaever, 1961. The zone is divided (Fig. 2) into the *Globorotalites emdyensis* s. str., *Bolivinoides draco miliaris*, and *Brotzenella taylorensis* subzones, which correspond to zones BF5, BF6, and BF7 in the scheme of Beniamovskii and Kopaevich, (1998). The lower zonal boundary is defined at the first occurrence level of the index species in association with *Heterostomella foveolata* (Marss.) and *Orbignyina pinguis* Wolosch. The base of *Bolivinoides draco miliaris* Subzone corresponds to the appearance level of this subspecies and associated taxa *Eponides frankei* Brotz., *Bolivina incrassata incrassata* (Reuss), and *B. kalinini* Vass. Indicative forms of the upper subzone are *Neoflabellina praereticulata* Hilt., *Osangularia navarroana* (Cushm.), *Stensioeina gracilis stellaria* Vass., *Brotzenella taylorensis* (Carsey), *Bolivinoides decoratus giganteus* Hilt. et Koch, and *Silicosigmoilina volganica* (Kuzn.).

The *Globorotalites emdyensis* Subzone corresponds to the *Belemnitella langei minor–Bostrychoceras polyplocum* Subzone of cephalopods. Equivalents of *Bolivinoides draco miliaris* and *Brotzenella taylorensis* subzones are the *Belemnitella langei langei–Didymoceras donezianum* Subzone and lower strata of the *Belemnitella langei najdini–Micraster grimmensis* Subzone, respectively.

The *Angulogavelinella gracilis* Zone initially recognized by Beniamovskii *et al.*, (1973) is terminal one in the Campanian Stage of the East European platform, though earlier (Naidin *et al.*, 1984a, 1984b; Beniamovskii *et al.*, 1988) its range was believed to be wider, spanning in addition the *Neoflabellina reticulata* Zone distinguished afterward (Beniamovskii and Kopaevich, 1998) and attributed to the lower Maastrichtian. In our zonation, the *Angulogavelinella gracilis* Zone is accepted as subdivision signifying appearance of its index species in association with *Spiroplectammina suturalis* Kalin., *Cuneus minutus* (Marss.), *Bolivinoides delicatulus* Cushm., and *B. peterssoni* Brotz. Its assemblage also includes *Silicosigmoilina volganica* (Kuzn.) and *S. epigona* (Rzeh.)

The *Angulogavelinella gracilis* Zone is confidently correlated (Beniamovskii and Kopaevich, 1998) with the *Bolivinoides peterssoni–Globorotalites hiltermanni* Zone of northwestern Germany (Schönfeld, 1990), where the latter is attributed to the terminal part of the *Micraster grimmensis–Cardiaster granulosus* Zone that is the uppermost one in the Campanian Stage of western Europe. In the Russian plate, the *Angulogavelinella gracilis* Zone corresponds to the upper portion of the *Belemnitella langei najdini–Micraster grimmensis* Subzone and to the *Belemnella licharewi–Micraster grimmensis* Zone (*Prakticheskoe...*, 1991).

Maastrichtian Stage. The *Neoflabellina reticulata* Zone established by Koch (1977) is the lowermost one in the Maastrichtian Stage. It is defined by appearance of index species in association with *Heterostomella bullata* Akim., *Cibicidoides bembix* (Marss.), *Bolivina decurrens* (Ehr.), and *Pseudouvigerina cristata* (Marss.). Other characteristic forms of zonal assemblage are *Spiroplectammina suturalis* Kal., *Orbignyina pinguis* Wolosch., *O. sacheri* (Reuss), *O. inflata* (Reuss), *Stensioeina pommerana* Brotz., *Eponides frankei* Brotz., *Osangularia navarroana* (Cushm.), *Brotzenella menneri* (Kell.), *Cibicidoides beaumontianus* (Orb.), *C. aktulagayensis* (Vass.), *C. voltzianus* (Orb.), *Cuneus minutus* (Marss.), *Sitella laevis* (Vass.), *Bolivina incrassata incrassata* Reuss, *Bolivina kalinini* (Vass.), and *Bolivinoides delicatulus* Cushm. Taxa terminating their evolution at this level are *Globorotalites emdyensis* Vass., *Gavelinella clementiana laevigata* (Marie), and *Gemellides orcinus* (Vass.). The described zone corresponds to the lower part of the *Belemnella lanceolata* Subzone and is correlative with the subzone CC23a of calcareous nannoplankton.

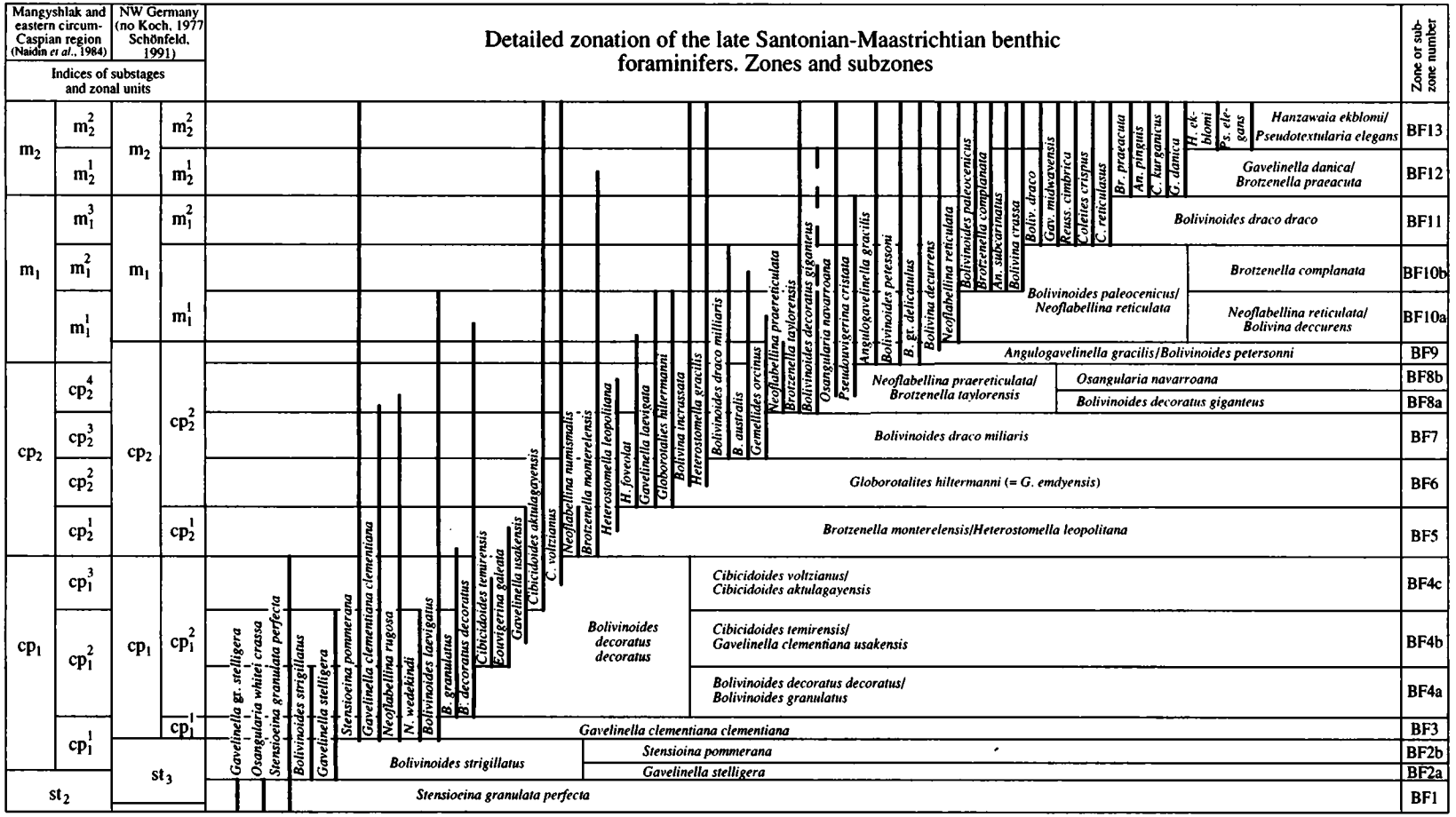

Fig. 2. Detailed zonation of the late Santonian–Maastrichtian benthic foraminifers (after Beniamovskii and Kopaevich, 1988, with modifications).

Table 5. Foraminiferal biozonations in the Mangyshlak–eastern circum-Caspian region (after Beniamovskii and Kopaevich, 1998, with modifications) and northwestern Germany correlated with the scheme suggested for the Russian platform

Mangyshlak and eastern circum-Caspian region		Northwestern Germany		Zonation of benthic foraminifers in the European paleobiogeographic province (Beniamovskii and Kopaevich, 1998)		Regional zones of benthic foraminifers				Zonation of benthic foraminifers in the Russian platform as suggested in this work	
						East European paleobiogeographic province		West European paleobiogeographic province			
Substages and their subordinate subdivisions						(Naidin *et al.*, 1984a, 1984b; Akimets *et al.*, 1991)		(Koch, 1977)	(Schönfeld, 1990)	Zones	Subzones and beds
m_2		m_2	m_2^2	*Hanzawaia ekblomi/Pseudotextularia elegans*	BF13	*Pseudotextularia elegans*	XXVI	*Pseudotextularia elegans*	*Pseudotextularia elegans* – I. Zone	*Brotzenella praeacuta – Hanzawaia ekblomi*	
			m_2^1	*Gavelinella danica/Brotzenella praeacuta*	BF12	*Brotzenella praeacuta*	XXV	*Gavelinella danica*			
m_1	m_1^3	m_1	m_1^2	*Bolivinoides draco draco*	BF11	*Bolivinoides draco draco*	XXIV	*Bolivinoides draco draco*	*paleocenicus/retuculata* P.R. Zone	*Brotzenella complanata*	*Bolivinoides draco draco*
	m_1^2			*Bolivinoides paleocenicus/Neoflabellina reticulata* / *Brotzenella complanata*	BF10b	*Brotzenella complanata*	XXII	*Neoftabellina reticulata*			*Brotzenella complanata*
	m_1^1		m_1^1	*Neoflabellina reticulata/Bolivina decurres*	BF10a	*Angulogavelinella gracilis*	XXII		*decurrens* – I. Zone	*Neoftabellina reticulata*	
		cp_2	cp_2^2	*Angulogavelinella gracilis/ Bolivinoides peterssoni*	BF9			*Bolivinoides draco miliaris*	*peterssoni/hiltermanni* – C.R. Zone	*Angulogavelinella gracilis*	
cp_2	cp_2^4			*Neoflabellina praereticulata/Brotzenella taylorensis* / *Osangularia navarroana*	BF8b	*Brotzenella taylorensis*	XXI		*navarroana/crista-ta* – P.R. Zone	*Globorotalites emdyensis*	*Brotzenella taylorensis*
	cp_2^3			*Bolivinoides decoratus giganteus*	BF8a				*miliaris/incrassata* – P.R. Zone		*Bolivinoides draco miliaris*
				Bolivinoides draco miliaris	BF7	*Bolivinoides draco miliaris*	XX		*gracilis* – P.R. Zone		*Globorotalites emdyensis*
	cp_2^2			*Globorotalites hiltermanni* (= *G. emdyensis*)	BF6	*Cibicidoides voltzianus*	XIX	*Neoflabellina numismalis*	*leopolitana* – P.R. Zone		
	cp_2^1		cp_2^1	*Brotzenella monterelensis/Heterostomella leopolitana*	BF5	*Brotzenella monterelensis*	XVIII		*laevigatus* – P.R. Zone	*Brotzenella monterelensis*	
cp_1	cp_1^3	cp_1	cp_1^2	*Bolivinoides decoratus decoratus* / *Cibicidoides aktulagayensis/C. voltzianus*	BF4c	*Cibicidoides aktulagayensis*	XVII	*Bolivinoides decoratus decoratus*	*voltzaianus* – P.R. Zone	*Cibicidoides temirensis*	*Cibicidoides aktulagayensis*
	cp_1^2			*Cibicidoides temirensis/Gavelinella clementiana usakensis*	BF4b	*Cibicidoides temirensis*	XVI		*granulatus* – P.R. Zone		*Cibicidoides temirensis*
				Bolivinoides decoratus decoratus/B. granulatus	BF4a	*Bolivinoides decoratus decoratus*	XV		*wedekindi* – P.R. Zone	?	
	cp_1^1		cp_1^1	*Gavelinella clementiana clementiana*	BF3	*Gavelinella clementiana clementiana*	XVI	*Bolivinoides strigillatus*	*clementiana* – P.R. Zone	*Gavelinella clementiana clementiana*	
									concinna – I Zone		
		st_3		*Bolivinoides strigillatus* / *Stensioeina pommerana*	BF2b	*Bolivinoides strigillatus*	XIII		*pommerana/frankei* P.R. Zone	*Gavelinella stelligera*	*Stensioeina pommerana*
st_2				*Gavelinella stelligera*	BF2a				*strigillatus* – P.R. Zone		*Gavelinella stelligera*
				Stensioeina granulata perfecta	BF1	*Stensioeina granulata perfecta*	XII	*Stensioeina granulata perfecta*	*perfecta* – P.R. Zone		

The *Brotzenella complanata* Zone was originally recognized by Grigyalis *et al.*, (1974), and its stratigraphic range was somewhat refined afterward (Akimets *et al.*, 1983). It includes the *Brotzenella complanata* s. str. and *Bolivinoides draco draco* subzones. Foraminiferal assemblage of the former is similar in general to that of the underlying zone, but newcomers *Brotzenella complanata* (Reuss) and *Bolivina incrassata crassa* Vass. represent its distinctive taxa. The lower subzone corresponds to the upper part of *Belemnella lanceolate* Subzone or to the subzone CC23b of calcareous nannoplankton. The upper subzone is established above the extinction level of subspecies *Bolivinoides draco miliaris* Hilt. et Koch that is replaced by subspecies *Bolivinoides draco draco* (Marss.) associated with *Gavelinella midwayensis* (Plum.). This subzone corresponds to the *Belemnella sumensis* Subzone and bears nannoplankton of the zone CC24.

The *Brotzenella praeacuta–Hanzawaia ekblomi* Zone it terminal one in the Maastrichtian Stage. In sections of northwestern Germany (Koch, 1977) and western Kazakhstan (Naidin *et al.*, 1984a, 1984b), there were distinguished, though under different names, two subzones of the unit (Table 5): the lower *Gavelinella danica* or *Brotzenella praeacuta* subzones and the upper *Pseudotextularia elegans* or *Hanzawaia ekblomi* subzones (in western or eastern regions, respectively). It is likely that in the eastern Russian plate (Ul'yanovsk and Saratov areas), the *Brotzenella praeacuta* and *Hanzawaia ekblomi* subzones can be recognized as separate subdivisions (Beniamovskii *et al.*, 1988; Dmitrienko *et al.*, 1988; Alekseev *et al.*, 1999), but they cannot be discriminated in the west so far.

The following taxa of benthic foraminifers are characteristic of the *Brotzenella praeacuta–Hanzawaia ekblomi* Zone: *Spiroplectammina suturalis* Kal., *S. kelleri* Dain, *S. kasanzevi* Dain, *Neoflabellina reticulata* (Reuss), *Stensioeina pommerana* Brotz., *S. caucasica* (Subb.), *Osangularia navarroana* (Cushm.), *Gavelinella affinis* (Hant.), *G. danica* (Brotz.), *G. midwayensis* (Plum.), *G. pertusa* (Marss.), *G. welleri* (Plum.), *Brotzenella complanata* (Reuss), *B. praeacuta* (Vass.), *Hanzawaia ekblomi* (Brotz.), *Cibicidoides beaumontianus* (Orb.), *C. bembix* (Marss.), *C. spiropunctatus* (Gall. et Marss.), *Anomalidoides pinguis* (Jenn.), *A. ukrainicus* (Wolosch.), *Karreria fallax* Rzeh., *Cuneus minutus* (Marss.), *Bulimina quadrata* Plum., *B. inflata* Seg., *Bolivina decurrens* Ehr., *B. plaita* Carsey, *Bolivinoides draco draco* (Marss.), *B. decoratus giganteus* Hilt. et Koch, *B. incrassata incrassata* Reuss, and *B. peterssoni* Brotz. It is remarkable that among concurrent planktonic forms there are present *Abathomphalus mayaroensis* (Bolli) and *Globotruncanita stuarti* (Lappar.), both identified by T.E. Ulanovskaya in the Maastrichtian sequence of the Pervomaiskaya–Chir monocline, the Rostov region. The described zone yields fossils characteristic of nannoplankton zones CC25 and CC26 (Alekseev *et al.*, 1999) and corresponds to the *Belemnitella junior–Neobelemnella kazimiroviensis* Zone of cephalopods.

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Conodonts in Xenoliths of Sedimentary Rocks from Kimberlite Pipes of the Daldyn–Alakit Area (Sakha)

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Abstract—Diverse conodont assemblages discovered in xenoliths of sedimentary rocks from kimberlite pipes are analyzed and correlated with zonal stratigraphic scales. Based on the original and published data, a Paleozoic rock sequence that existed in the area at the stage of pipe formation is reconstructed, and its stratigraphic hiatuses serving as criteria for exploration of diamonds are distinguished.

Key words: Daldyn–Alakit area, xenoliths of sedimentary rocks, Paleozoic deposits, conodonts.

INTRODUCTION

First data on occurrence of organic remains in the xenoliths of sedimentary rocks (XSR) in the Siberian platform are available from works by Milashev and Shul'gina (1959), Mikhailov and Gridasov (1963), and others who used the fossils to date the enclosing rocks. Later on, it was established that organic remains from the XSR bear an information that is useful for paleogeographic interpretations (Koval'skii *et al.*, 1969; Brakhfogel' *et al.*, 1975; Brakhfogel', 1984; and others). Brakhfogel' (1984) who sampled during many years and summarized materials on macrofossils from the XSR presented data on 40 dated xenoliths from the Daldyn–Alakit area. Assemblages of organic remains are dominated by Early Silurian tabulates and brachiopods, most interesting among which are Pragian, Givetian, and Frasnian forms. At present, the corresponding deposits are missing from the Daldyn–Alakit area. Brakhfogel' reconstructed the past succession of Ordovician, Silurian, and Devonian deposits of the area and assumed that there were prolonged (Late Silurian–Early Devonian and Late Devonian–Early Carboniferous) and brief (Early–Middle Ordovician and Early–Middle Devonian) hiatuses in the succession (Fig. 3). In the light of the concept that kimberlite magmatism is confined to the rising periods of ancient platforms the area was considered to be promising for the discovery of kimberlite fields related to the defined hiatuses (Brakhfogel', 1984). It is difficult to discriminate epochs of kimberlite formation using radiological methods because they are divided by short time ranges. At present, seven corresponding epochs are recognized in the Siberian platform (Davis *et al.*, 1980). Regular investigations of conodonts from the XSR in kimberlite pipes of the Daldyn–Alakit area (Fig. 1) initiated by D.L. Smirnov and backed by F.F. Brakhfogel' to confirm radiological ages were carried out since 1991. This fossil group appeared to be most informative for age determination of sedimentary xenoliths.

An accurate age determination of conodont assemblages from the XSR is possible by means of their correlation with available Ordovician and Silurian zonal scales elaborated for the Siberian platform (Moskalenko, 1983, 1984) and with the standard Devonian zonal scale. The targeted sampling of xenoliths yielded a representative conodont collection that makes it possible to reconstruct those intervals of the Paleozoic section, which contain scarce macrofossils or lack them at all. Given below is the analysis of conodont assemblages from the XSR sampled from 11 kimberlite pipes of the Daldyn–Alakit area (Fig. 1).

MATERIALS

Pipe AKAR-S. One XSR sample with conodonts *Aphelognathus pyramidalis* (Branson, Mehl et Branson) and *Panderodus* sp. has been collected from this pipe. The first species is an index form of the synonymous zone defined in the Bur Horizon of the study area (Moskalenko, 1983, 1994).

Pipe Dal'nyaya. Three of eight samples collected from the pipe contain conodonts. Samples Dl-1 and Dl-4 yielded conodont forms *Drepanodistocodus vistrix* Mosk., *Panderodus* sp., *Dolborodina* gen. et sp. indet. Mosk. characteristic of the *Ozarkodina dolborica* Zone, which corresponds to the uppermost part of the Ashgillian Dolbor Horizon. This assemblage is well known in the Podkamennaya Tunguska River basin and Baikit area (Moskalenko, 1994). Sample Dl-5 encloses simple cone-shaped elements *Panderodus* sp. of a very wide stratigraphic range from the Middle Ordovician to Middle Devonian.

Pipe Dolgozhdannaya. Four of five samples from this pipe enclose the relatively diverse conodont assem-

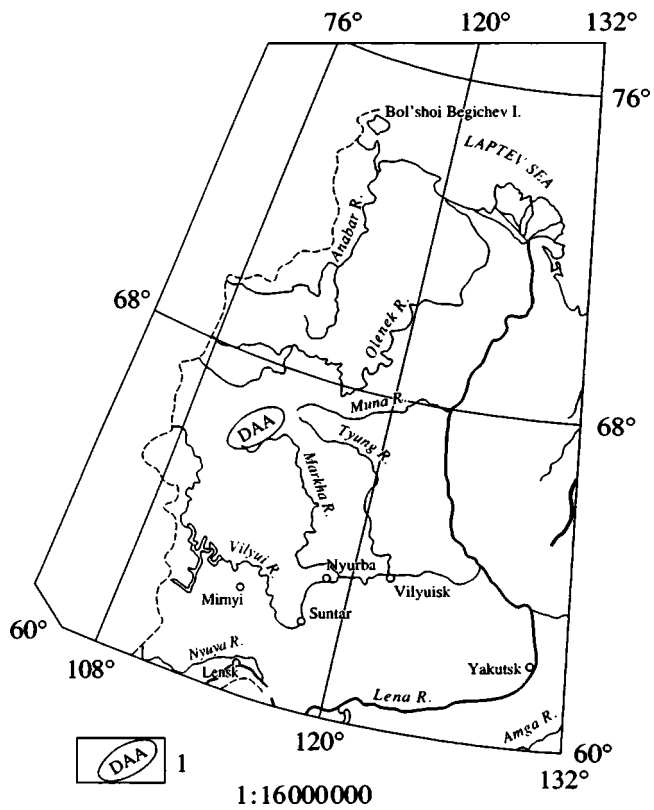

Fig. 1. Location of the study area: (1) boundary of the Daldyn–Alakit area (DAA).

blages. Samples Do-1, Do-4, and Do-5 yielded *Distomodus kentuckyensis* Branson et Branson, *Exochognathus caudatus* (Wall.), *Panderodus* sp., and *Icriodella* sp. This assemblage suggests the Llandoverian age of sedimentary xenoliths. It is widespread in coeval deposits of the Siberian platform (Tesakov *et al.*, 1986) and is known from the Llandovery–early Wenlock of Europe, America, and Asia (Aldridge, 1972; Cocks *et al.*, 1983). Another very peculiar conodont assemblage that consists of *Polygnathus linguiformis linguiformis* Hinde, *P.* aff. *linguiformis* Hinde, *Icriodus* sp. 1, and *I.* aff. *difficilis* Ziegler et Klapper was found in Sample Do-3. Its first species of a wide stratigraphic range is recorded in upper Emsian–lower Frasnian deposits of Europe, North America, Asia, and Australia (Klapper *et al.*, 1977). The last species is very close to true *Icriodus difficilis* Ziegler et Klapper whose stratigraphic range is limited by the Givetian–lower Frasnian in Northeastern Asia (Gagiev *et al.*, 1987). Thus, the age of enclosing rock is estimated to be the Givetian–early Frasnian. The total stratigraphic range of all four xenoliths spans the Lower Silurian (Llandovery) to Late Devonian (lower Frasnian) interval.

Pipe Zarnitsa. Conodonts are found in 15 of total 24 xenolith samples collected from this pipe. The oldest conodont assemblage from Sample Zr-5/93 includes *Drepanoistodus suberectus* (Branson et Mehl), *Oneotodus variabilis* Lind., and *Glyptoconus quadriplicatus* (Branson et Mehl.), all characteristic of the Arenigian Kimai Horizon of the Siberian platform (Moskalenko, 1983). Samples Zr-1/93, Zr-7/94, 94370-4, and 94370-10 contain *Aphelognathus pyramidalis* (Branson, Mehl et Branson), *Acanthodina nobilis* Mosk., *Pseudobelodina*(?) *repens* (Mosk.), *Tetraprioniodus elegans* Mosk., and *Panderodus* sp. This assemblage is typical of the Ashgillian *Aphelognathus pyramidalis* Zone. The diverse conodont assemblage is present in Samples Zr-2/93, Zr-2/94, and 94370-1. Based on the occurrence of *Distomodus kentuckyensis* Branson et Branson and *Exognathus caudatus* (Wall.), both known from Assemblage 1 defined in the Moierokan Formation of the Arctic Siberian platform (Tesakov *et al.*, 1986), the host rocks are dated back to the Early Silurian. Sample 94370-9 contains fragments of conodonts morphologically very similar to species *Aulacognathus bullatus* (Nic. et. Rex.) from the Llandovery of Europe, North America, Asia, and the Khaastyr Formation (Llandovery) of the Siberian platform (Tesakov *et al.*, 1986). The age of Sample 94370-11 is estimated to be the Early Devonian based on the occurrence of *Pandorinellina philipi* (Kl.), the species widespread in the late Lochkovian and Pragian deposits of Asia, North America, and Australia (Klapper *et al.*, 1973). The youngest conodont assemblage of *Polygnathus decorosus* Stauf., *P. dubius* Hinde, *P.* aff. *webbi* Stauf., and *Icriodus* sp. was obtained from Sample 94370-7. The stratigraphic range of the first species is limited by the Frasnian (Barskov *et al.*, 1971). Other species are of a wider range, occurring from the Givetian (the *varcus* Zone) to the lower Frasnian (the *asymmetricus* Zone). The total stratigraphic range of all samples from the pipe is the Lower Ordovician (Arenigian)–Upper Devonian (Frasnian).

Pipe Leningradskaya. Conodonts occur in four of nine samples of sedimentary xenoliths. Sample Ld-9 is confidently of the Ashgillian age, as it is established based on the presence of single P_b-element of species *Aphelognathus pyramidalis* (Branson, Mehl et Branson). Samples Ld-1 and Ld-2 yielded *Distomodus kentuckyensis* Branson et Branson, *Exochognathus caudatus* (Wall.), *Ozarkodina* sp., and *Panderodus* sp., all characteristic of the Llandoverian Moierokan Formation. The Middle Devonian age of Sample Ld-7 is inferred from the joint occurrence of *Polygnathus linguiformis linguiformis* Hinde morphotype *beta* Bultynck and *Icriodus difficilis* Ziegler et Klapper. The stratigraphic range of the former species is restricted by the Givetian (the *varcus* Zone). It is widespread in Givetian deposits of Asia, Europe, and North America (Klapper *et al.*, 1977). The integral stratigraphic range of all samples from the pipe spans the Upper Ordovician (Ashgillian)–Middle Devonian (Givetian) interval.

Pipe Prognoznaya. Four of ten xenolith samples from this pipe contain conodonts. Sample Pr-2 yields species *Scandodus warendensis* (Dr. et Jon.), *Scolopodus quadriplicatus* Branson et Mehl, *"Paltodus"*

bassleri (Furn.), and others. Beyond the study area, all of them occur only in the Lower Ordovician successions and are characteristic of the Arenigian Ugor and Kimai horizons of the Siberian platform (*Nizhnii...*, 1987). According to peculiar form *Phragmodus flexuosus* Mosk. present in Sample Pr-1, the host-rock age is estimated to be the Llandeilian (corresponds to the Volgino Horizon). This species of a narrow stratigraphic range and wide geographic distribution is recorded in the Llandeilian deposits and their age analogues of North America and Asia (Moskalenko, 1973; 1983; 1994). Sample Pr-9 yielded an assemblage that includes *Drepanoistodus suberectus* (Branson et Mehl) and *Panderodus* sp. Both forms have wide stratigraphic ranges: the Lower–Upper Ordovician and Middle Ordovician–Middle Devonian, respectively. Coexistence of these taxa implies that their host rock is of the Caradocian–Ashgillian age. Species *Acanthocordylodus fidelis* Mosk. identified in Sample Pr-6 is widespread in the Ashgillian Dolbor Horizon and less common in younger deposits (Moskalenko, 1994). The stratigraphic intervals of all XSR from the pipe is estimated to be corresponding to the Ordovician.

Pipe Sytykanskaya. Five of 15 of xenoliths collected from this pipe yielded conodonts. The Lower Ordovician assemblage identified in Sample St-15 includes *Oneotodus variabilis* Lind. and *"Paltodus" bassleri* Furn., which are known from the Tremadocian Nyai and Arenigian Ugor horizons of the Siberian platform (*Nizhnii...*, 1987). Sample St-4 contains *Aphelognathus* sp. and *Tetraprioniodus elegans* Mosk. The last form has been described from the Dolbor Horizon (Moskalenko, 1973) and is also recorded in the Ashgillian deposits of the Selennyakhskii (Tarabukin, 1994) and Sette-Daban ridges. Elements of *Exognathodus caudatus* (Wall.), the species characteristic of the Lower Silurian Moierokan Formation (Tesakov *et al.*, 1986), occur in Samples St-5, St-7, and St-10. The total stratigraphic range of conodonts from all samples corresponds to the Lower Ordovician–Lower Silurian.

Pipe Udachnaya-Vostochnaya. Until present, no data are available on organic remains in the XSR from this pipe. Three of eight samples in my collection from the pipe yielded however the Lower and Upper Ordovician conodonts. Sample UV-1 contains *Polycostatus oneotensis* Furn. and *Drepanoistodus forceps* (Lind.). The first species that is known from the Nyai and Ugor horizons of the Siberian platform (*Nizhnii...*, 1987) and from the local Canadian Stage of North America occurs throughout the Lower Ordovician (Tremadocian–Arenigian) only. Taking into consideration the first occurrence of this species in the Arenigian (Lindstrom, 1971), the enclosing rock is estimated to be of the same age. Elements of *Aphelognathus pyramidalis* (Branson, Mehl, et Branson) that is the index species of the synonymous zone and coexisting peculiar taxa *Acanthodina nobilis* Mosk. and *Phragmodus(?) tunguskiensis* Mosk. imply the Late Ordovician–Ashgillian age of samples UV-5 and UV-7 (Moskalenko, 1973, 1983).

Pipe Udachnaya-Zapadnaya. The pipe is remarkable for abundance of organic remains in the XSR, and 14 of 25 samples from the studied collection contain conodonts. Elements of *Acanthodina nobilis* Mosk., *Acanthocordylodus fidelis* Mosk., and *Aphelognathus pyramidalis* (Branson, Mehl, et Branson) typical of the Ashgillian Bur Horizon (Moskalenko, 1984) have been macerated from samples UZ-12/94, 94368-4, 9436-7, and 94368-8. Samples UZ-5/94, UZ-7/94, 94368-2, 94368-5, and 94368-11 are dated back to the Llandovery (Lower Silurian) based on the occurrence of *Distomodus kentuckyensis* (Br. et. Br.), *Exognathus caudatus* (Wall.), and other forms characteristic of the Moierokan Formation (Tesakov *et al.*, 1986). *Pandorinellina philipi* (Kl.) accompanied in Sample 94368-7 by broken poorly preserved elements of *Icriodus* sp., *Ozarkodina* sp., and *Panderodus* sp. is widespread in the Lower Devonian (upper Lochkovian and Pragian) deposits of North America and Asia (Klapper *et al.*, 1973). Taking into consideration stratigraphic ranges of taxa *Polygnathus linguiformis linguiformis* Hinde and *Icriodus difficilis* Ziegler et Klapper (Barskov *et al.*, 1991; Ziegler *et al.*, 1977) occurring in samples UZ-6/94, UZ-13/94, 94368-13, and 94368-15, their host rocks can be dated back to the Givetian–early Frasnian. The integral stratigraphic range of samples from the pipe in question is the Upper Ordovician–Upper Devonian.

Pipe Yubileinaya. Eleven of 22 samples from the pipe bear conodonts. The assemblage of *Acontiodus staufferi* Furn. *Drepanoistodus suberectus* (Branson et Mehl), *"Paltodus" bassleri* Furn., and other forms identified in samples Yub-5/93 and Yub-6/94 is characteristic of the Arenigian Ugor Horizon (*Nizhnii...*, 1987). Samples Yub-6/93, Yub-5/94, and 94369-4 yield elements of *Aphelognathus* sp., *Pseudobelodina(?) repens* (Mosk.), *Tetraprioniodus elegans* (Mosk.), and other taxa typical of the Ashgillian Bur Horizon of the Siberian platform (Moskalenko, 1983, 1994), whereas *Exognathodus caudatus* (Wall.) and other forms characteristic of the Llandoverian Moierokan Formation (Tesakov *et al.*, 1986) occur in samples Yub-1/94, 94369-7, and 94369-11. Limestone with large tabulate colonies (Sample Yub-77 from collection of F.F. Brakhfogel') yielded *Walliserodus curvatus* (Branson et Branson) and a fragment of conodont with a peculiar ornamentation that has been identified as P_a-element of *Distomodus staurognathoides* (Wall.). Both species have been reported from the Llandoverian Haastyr Formation (Tesakov *et al.*, 1986). A very peculiar form found in Sample Yub-3/94 was previously identified in the open nomenclature as gen et sp. indet. from the upper Llandoverian–Wenlockian Agidy Formation (Tesakov *et al.*, 1986). The Middle–Late Devonian age of sedimentary xenoliths from this pipe is confirmed by finds of *Polygnathus linguiformis linguiformis* Hinde and *Icriodus* sp. (Sample Yub-1/94) whose stratigraphic range corresponds to the Givetian–lower Frasnian (Barskov *et al.*, 1991). Thus, the integral stratigraphic range

of samples from the pipe under consideration corresponds to the Lower Ordovician–Upper Devonian.

Pipe Yakutskaya. Only four of 15 examined samples from this pipe contain conodonts. Species *Drepanodistacodus vistrix* (Mosk.) and *Drepanodistodus suberectus* (Branson et Mehl) from Sample Yak-3/93 are of a wide stratigraphic range and coexist with a form identified as *Phragmodus* aff. *flexuosus* (Mosk.). This form that cannot be determined as nominal species because of broken P_b-element suggests however the Middle Ordovician (Llandeilian?) age of host rock, if we take into consideration that the true species is characteristic of the Volgino Horizon. Sample Yak-15/93 yielded a relatively diverse assemblage consisting of *Aphelognathus pyramidalis* (Branson, Mehl et Branson), *Acanthodina nobilis* Mosk., *Acanthocordylodus* sp., *Tetraprioniodus* sp., and other forms characteristic of the Bur Horizon (Moskalenko, 1994). Coexistence of *Distomodus kentuckyensis* (Branson et Branson) and *Exognathus caudatus* (Wall.) indicates the Llandoverian age of Sample Yak-1/93 (Tesakov *et al.*, 1986). Sample Yak-2/93 yielded *Pterospathodus* aff. *amorphognathoides* Wall. known from the Llandoverian–lower Wenlockian Agidy Formation (Tesakov *et al.*, 1986).

ANALYSIS OF CONODONT ASSEMBLAGES

The thorough analysis of conodonts from sedimentary xenoliths and their stratigraphic ranges reveals 10 different-age assemblages. The oldest one is established in xenoliths from the pipe Sytykanskaya (Sample St-15). It includes *Oneotensis variabilis* Lind. and *"Paltodus" bassleri* Furn. characteristic of the Tremadocian Nyai and Arenigian Ugor horizons of the Siberian platform (*Nizhnii...*, 1987).

The second assemblage composed of *Acanthodina staufferi* (Furn.), *Drepanoistodus forceps* (Lind.), and *Oneotensis variabilis* Lind. is similar to that from the Ugor Horizon of the Siberian platform and *Scolopodus(?) abberans* Beds (Moskalenko, 1983). It is characteristic of xenoliths from the pipes Zarnitsa (Sample Zr-5/93), Udachnaya-Vostochnaya (Sample UV-1), and Yubileinaya (Sample Yub-5/93).

The assemblage of *Glyptoconus quadriplicatus* (Branson et Mehl), *"Paltodus" bassleri* Furn., and *Scandodus warendensis* (Dr. et Jon.) was found only in Sample Pr-2 from the pipe Prognoznaya. It is typical of the Kimai Horizon and can be correlated with the *Glyptoconus quadraplicatus–Histiodella angulata* Zone.

The assemblage with *Phragmodus flexuosus* Mosk., *Ph.* aff. *flexuosus* Mosk. *Drepanodistacodus vistrix* Mosk., and *Drepanoistodus suberectus* (Branson et Mehl.), the first of which is the index species of the synonymous zone of the Volgino Horizon widespread in the Siberian platform (Moskalenko, 1983, 1994), has been identified in xenoliths from the pipes Prognoznaya (Sample Pr-1) and Yakutskaya (Sample Yak-3/93).

Xenoliths from the pipes Dal'nyaya, Prognoznaya, and Yubileinaya contain the assemblage of *Acanthocordylodus fidelis* Mosk., Dolborodina gen. et sp. indet., Mosk., and *Panderodus* sp. The assemblage is typical of the Caradocian Dolbor and Ashgillian Bur horizons of the Siberian platform, which correspond to the *Acanthocordylodus festus, Ozarkodina? dolboricus*, and *Acanthodina nobilis* zones (Moskalenko, 1983, 1994).

Most common in the XSR is a peculiar Ashgillian conodont assemblage with *Aphelognathus pyramidalis* (Branson, Mehl et Branson), the index species of synonymous zone in the Siberian platform (Moskalenko, 1994). In addition to the latter, the assemblage includes *Acanthocordylodus fidelis* Mosk., *Acanthodina nobilis* Mosk., *Panderodus* sp., *Pseudobelodina(?) repens* (Mosk.,), and *Tetraprioniodus elegans* (Mosk.). The assemblage characterizes xenoliths from eight pipes, except for the Dal'nyaya, Dolgozhdannaya, and Prognoznaya pipes.

Most widespread are xenoliths of the Lower Silurian limestones with conodonts *Exognathodus caudatus* (Wall.), *Distomodus kentuckyensis* (Branson et Branson), *Icriodella* sp., *Ozarkodina* sp., and *Panderodus* sp. These conodonts common in the Llandoverian–Wenlockian Moierokan Formation of the Siberian platform were formerly united into Assemblage 1 (Tesakov *et al.*, 1986).

The Llandoverian Assemblage 2 (Tesakov *et al.*, 1986) occurs only in xenoliths from the pipes Yubileinaya and Yakutskaya. It consists of *Distomodus staurognathoides* (Wall.), *Pterospathodus* aff. *amorphognathoides* Wall., and *Walliserodus curvatus* (Branson et Branson). The assemblage is correlative to the Khaastyr Formation of the northern Siberian platform.

The pipes Zarnitsa and Udachnaya-Zapadnaya bear xenoliths with the Early Devonian conodont assemblage consisting of *Icriodus* sp., *Ozarkodina* sp., and *Pandorinellina philipi* (Kl.). At present, the Devonian deposits are locally exposed only in the northwestern Siberian platform.

The Givetian–Frasnian conodont assemblage of *Icriodus difficilis* Ziegler et Klapper, *L.* aff. *difficilis* Ziegler et Klapper, *Panderodus* sp, and *Polygnathus linguiformis linguiformis* Hinde is established in xenoliths from the pipes Dolgozhdannaya, Zarnitsa, Leningradskaya, Udachnaya-Zapadnaya, and Yubileinaya. It implies that Middle–Upper Devonian deposits were widespread in the Siberian platform.

There are several stages of kimberlite formation defined in the Siberian platform, one of which is thought to be correlative with the pre-Silurian hiatus. The data obtained reveal that the Upper Ordovician–Lower Silurian rock sequence was of an intricate structure. The studied core materials allowed elaboration of the Ordovician stratigraphic scheme of the Aikhala area (*Nizhnii...*, 1987). According to the scheme, the rock sequence in the area is almost lacking deposits of the Nirunda, Dolbor, and Bur horizons. Conodont assem-

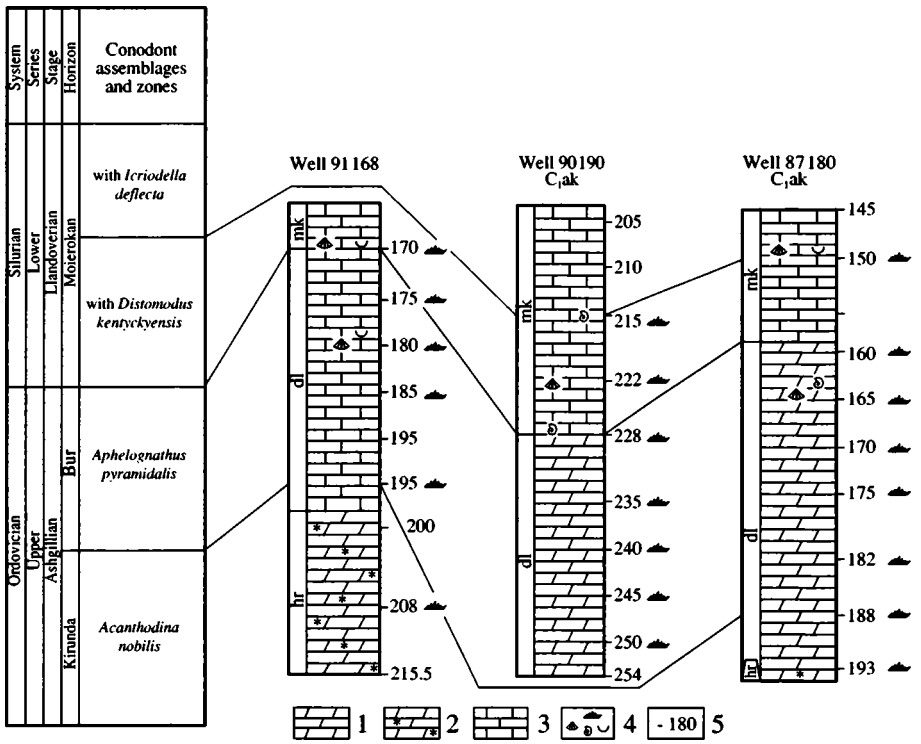

Fig. 2. Correlation of sections drilled at the Pravoberezhnyi site: (1) marl; (2) variegated marl; (3) limestone; (4) fossils; (5) sample numbers (corresponding to depths in wells); (hr) Khar'yalakh Formation; (dl) Delingda Formation; (mk) Meik Formation.

blages characteristic of the Bur Horizon were found only in cores from wells drilled at the Pravoberezhnyi site (Moskalenko, 1983, 1994; *Nizhnii...*, 1987). My subsequent examination of cores from Wells 87180, 90190, and 91168 drilled in this area on the right bank of the Markha River (Fig. 2) confirmed the validity of the above-mentioned scheme. Simultaneously, conodont assemblages of the Llandoverian age were detected. Wells penetrated in this area the Kharal'yakh Formation composed of variegated marls, the Delengda Formation of clayey limestones and marls with rare organic remains, and the Meik Formation of organogenic limestones with a minor clay admixture.

Three conodont assemblages corresponding to the Ordovician Bur Horizon and the Llandoverian Stage were defined in the examined cores. The presence of the Bur Horizon in the sequence is indicated by the conodont assemblage of the *Aphelognathus pyramidalis* Zone in the intervals of 208 to 175, 254 to 235, and 195 to 154.5 m of wells 91168, 90190, and 87180, respectively (Fig. 2). Most important in the assemblage is the index species widespread in the northern Siberian platform (Moskalenko, 1983, 1994). In the Daldyn–Alakit area, deposits of this horizon are preserved only in some places. The Lower Silurian conodont assemblage differs significantly from the Upper Ordovician one. The intervals of 170–200, 228–215, and 160–150 m in wells 91168, 90190, and 87180, respectively, yielded the conodont assemblage with dominant *Distomodus kentuckyensis* typical of the Llandovery of the Siberian platform (Tesakov *et al.*, 1986). Stratigraphically higher (intervals of 170–165, 215–203, and 150–145 in wells 91168, 90190, and 87180, respectively), there are the *Icriodella deflecta* Beds with elements of the their index species, *Aulacognathus bullatus* (Nicoll et Rexroad), and other forms. The Middle Carboniferous Aikhala Formation overlying these deposits with a stratigraphic unconformity lacks conodonts.

INVESTIGATION PROCEDURE

When studying conodonts from the XSR and some sections in the Daldyn–Alakit area, I paid main attention to paleontological substantiation and correlation of distinguishable units with those of other sections in order to reconstruct the true succession of sedimentary rocks that formerly existed in the area. Pipes were originally sampled by conventional method and then using a special method that significantly increases the objective character and efficiency of sampling. The method was directly tested in the pipes Udachnaya, Yubileinaya, and Zarnitsa.

THE XSR DISTRIBUTION WITHIN A PIPE

Xenoliths are chaotically distributed in a pipe. The revealed distribution patterns show that xenoliths of country rocks prevail in the peripheral parts of pipes.

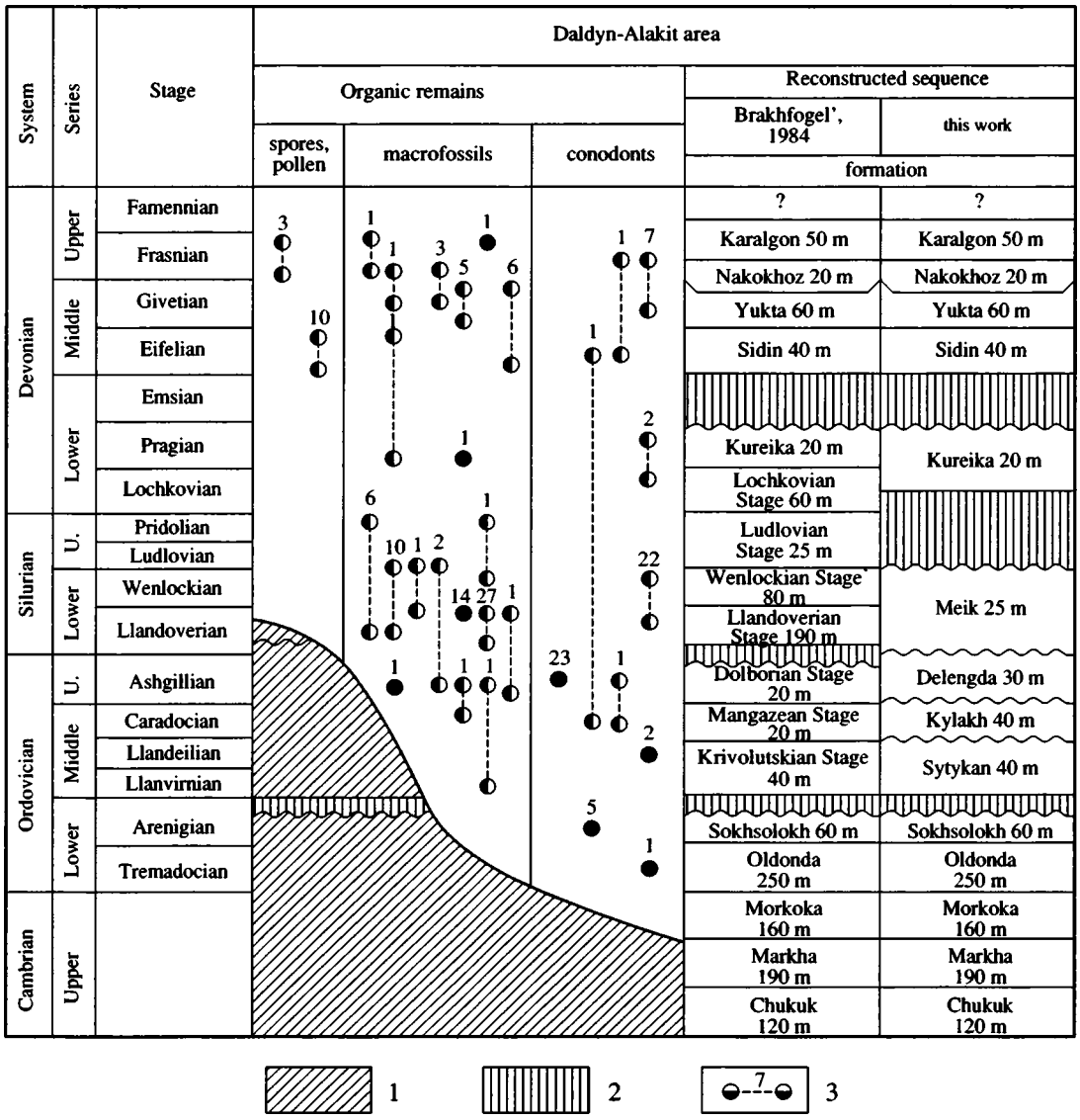

Fig. 3. Reconstructed Paleozoic sections of the Daldyn–Alakit area and their biostratigraphic substantiation. (1) bedrocks; (2) hiatus; (3) stratigraphic range of xenoliths with paleontological remains; (u) upper; (f) formation.

Regularities in vertical distribution of xenoliths have not been specially studied, but it is clear nevertheless that different-age conodont assemblages may occur at a single level. According to available data (Hawthorne, 1975), the vertical (mainly downward) displacement of rock fragments within some pipes exceeds 1500 m. The XSR (Samples L-7 and L-A) from the pipe Lorik at the right bank of the Olenek River bear the upper Tournaisian conodont assemblage, although the pipe itself is surrounded by the exposed Middle Cambrian rocks. In this case, xenoliths could be displaced for 400 m downward. Their upward displacement in a pipe is difficult to estimate, because most of the studied pipes have not been ever drilled or excavated in quarries. At present, such a displacement can be evaluated for the Zarnitsa and Prognoznaya pipes only, the exposures of which are surrounded by deposits of the Lower Silurian Meik Formation. The XSR from these pipes yielded Lower Ordovician conodonts. Calculations show that they should be transported upward for 80–100 m.

CONCLUSIONS

The thorough paleontological analysis of conodont assemblages from the XSR was used to substantiate reconstruction of Paleozoic sediment succession in the study area (Fig. 3). The obtained data confirm the earlier assumptions that there are several hiatuses in the inferable rock sequence: at the Lower–Middle Ordovician boundary, within the Middle Ordovician, at the base of the Chertov Horizon, Early–Middle Devonian, and the Late Devonian–Early Carboniferous. Succes-

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Plate 1. Conodonts from sedimentary xenoliths of kimberlite pipes and from rocks of the Pravoberzhnyi site, the Daldyn–Alakit area.

(1) *Exochognathus caudatus* (Walliser), Specimen 94370-5-1, side view, ×60, P-element, pipe Zarnitsa, Lower Silurian, Llandovery Stage; (2, 7, 9, 12) *Acanthodina nobilis* Moskalenko: (2) Specimen 87180-188-10, back view, ×50, (7) Specimen 87180-188-14, side view, ×40, (9) Specimen 90190-235-11, back view, ×30, Well 87180, depth 188 m, Well 90190, depth 235 m, upper reaches of the Markha River, Pravoberezhnyi site, Upper Ordovician, Ashgillian Stage, Delingda Formation, (12) Specimen Yak-15-7, side view, ×35, pipe Yakutskaya, Upper Ordovician, Ashgillian Stage; (3) *Exognathus caudatus* (Walliser), Specimen 94370-1-5, side view, ×35, pipe Zarnitsa, Lower Silurian, Llandovery; (4, 13) *Ptilognathus* sp.: (4) Specimen Yak-15-1, frontal view, ×50, pipe Yakutskaya, Upper Ordovician, Ashgillian Stage (13) Specimen Yak-15-2, back view, ×55, pipe Yakutskaya, Upper Ordovician, Ashgillian Stage; (5, 14) *Aphelognathus pyramidalis* (Branason, Mehl et Branson): (5) Specimen 94370-10-21, back view, ×40, S_b-element, (14) Specimen 94370-10-18, side view, ×45, P_b-element, pipe Zarnitsa, Upper Ordovician, Ashgillian Stage; (6) *Acanthocordylodus fidelis* Moskalenko, Specimen Pr-6-1, side view, ×35, pipe Prognoznaya, Upper Ordovician, Ashgillian Stage; (8) *Tetraprioniodus elegans* Moskalenko, Specimen St-4-4, side view, ×35, pipe Sytykanskaya, Upper Ordovician, Ashgillian Stage; (10) *Panderodus* sp., Specimen Ld-2-11, side view, ×40, pipe Leningradskaya, Lower Silurian, Llandovery; (11) *Oneotodus variabilis* Lindström, Specimen St-15-3, back view, ×40, pipe Sytykanskaya, Upper Ordovician, Tremadocian Stage; (15–17) *Icriodus* sp 1: (15) Specimen 94369-5-3, downward view, ×50, (16) Specimen 94369-15-4, downward view, ×50, (17) Specimen 94369-15-5, downward view, ×45, pipe Yubileinaya, Middle–Upper Devonian, Givetian–Frasnian; (18) *Icriodus* aff. *difficilis* Ziegler et Klapper, Specimen Do-3-15, downward view, ×45, pipe Dolgozhdannaya, Middle–Upper Devonian, Givetian–Frasnian; (19) *Polygnathus linguiformis linguiformis* Hinde, Specimen 94369-15-1, downward view, ×40, pipe Yubileinaya, Middle–Upper Devonian, Givetian–Frasnian; (20) *Icriodus difficilis* Ziegler et Klapper, Specimen Ld-7-3, downward view, ×60, pipe Leningradskaya, Middle–Upper Devonian, Givetian–Frasnian; (21) *Icriodus* sp. 2, Specimen 94370-7-16, side view, ×60, pipe Zarnitsa, Middle–Upper Devonian, Givetian–Frasnian; (22) *Pandorinellina philipi* (Klapper), Specimen 94370-11-7, side view, ×60, P-element, pipe Zarnitsa, Lower Devonian, Lochkovian–Pragian.

sion of conodont assemblages and lithology of rocks exposed in the Daldyn–Alakit area indicates that the hiatus at the Ordovician–Silurian boundary is either very short or missing at all. The age of pipe formation can be determined, based on organic remains from the XSR and with due account for detailed paleogeographic reconstructions, only if the extensive materials on different fossil groups are available. It should be emphasized that an important role belongs to microfossils, particularly to conodonts, because they are well preserved (Plates 1, 2).

Genus *Belodina* Ethington, 1959

Belodina brakhfogeli Tarabukin sp. nov.

Plate 1, Fig. 4

Etymology. The species is named in honor of geologist F.F. Brakhfogel'.

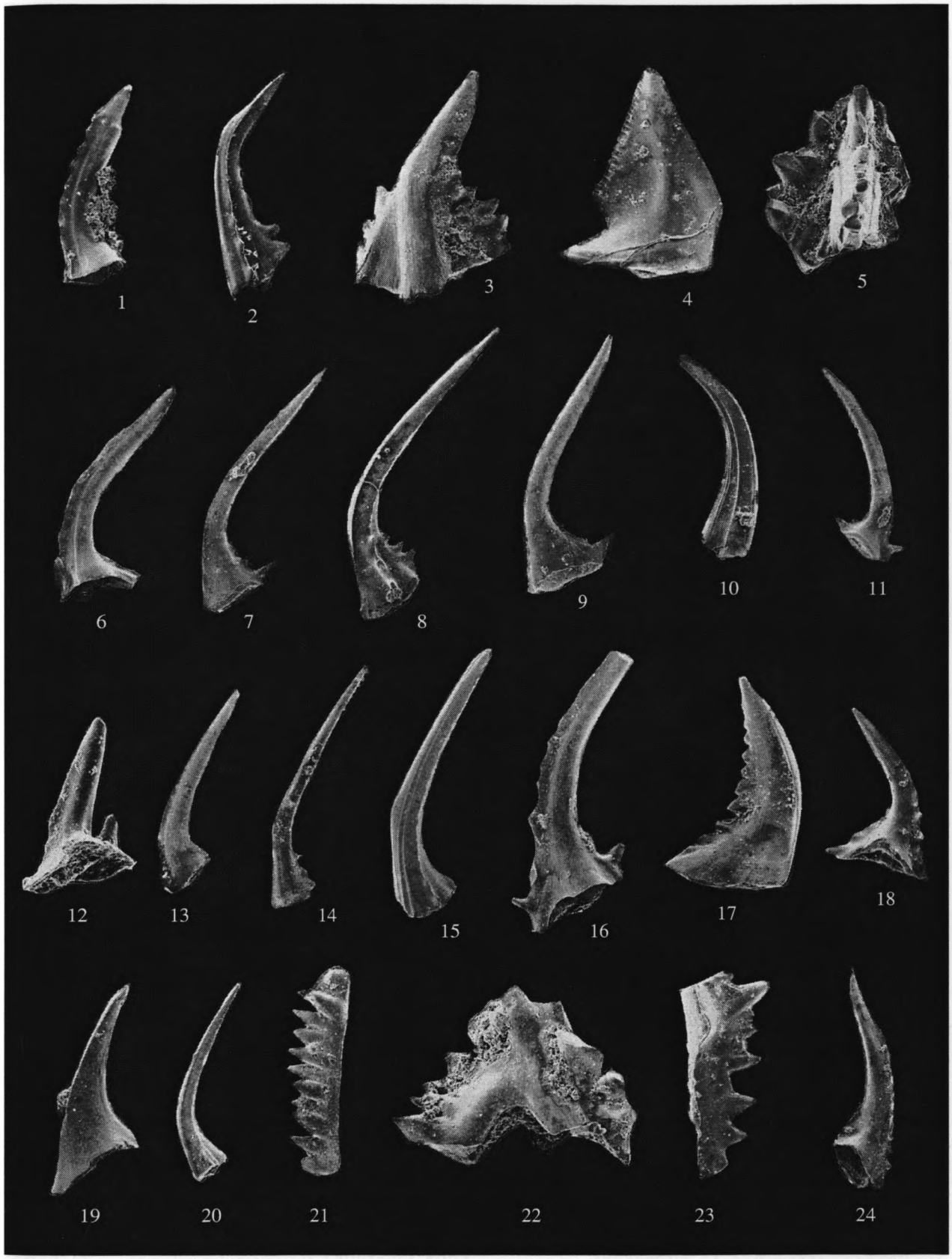
Holotype: no. 173/90190/235-19, Geological Museum of the Yakutsk Institute of Diamonds and Precious Metals, Yakutsk Scientific Center, Russian Academy of Sciences; Siberian platform, upper reaches of the Markha River, Pravoberezhnyi site, Ashgillian Stage, Delingda Formation, *Aphelognathus pyramidalis* Zone.

Diagnosis: P_a-element flat, with a high base, smoothly passing into a cusp; the base of the cusp with several closely spaced denticles; deep basal cavity, double-coned; P_b-element flat with a high base, passing with a bent into a cusp; deep basal cavity.

Description. P_a-elements are flat, slightly widened in the lower part. The cusp is high, wide, strongly inclined backward, and elongated almost perpendicularly to the basal edge (base). The line of the anterior edge is smoothly curved. The inner side of the cusp is flat and smooth. The outer side is slightly convex, with

Plate 2. Conodonts from sedimentary xenoliths of kimberlite pipe Yubileinaya and from rocks of the Pravoberzhnyi site, the Daldyn–Alakit area.

(1, 6, 11, 13, 16, 18, 24) *Acanthodus nobilis* Moskalenko: (1) Specimen 87180/188-5, back view, ×35, (6) Specimen 87180/188-9, back view, ×30, (11) Specimen 87180/193-7, back view, ×24, (13) Specimen 87180/188-8, back view, ×20, (16) Specimen 87180/188-15, back view, ×35, (18) Specimen 87180/165-10, side view, ×45, (24) Specimen 87180/188-4, back view, ×24; Well 87180/165, upper reaches of the Markha River, Pravoberezhnyi site, Upper Ordovician, Ashgillian Stage, Delingda Formation; (2, 8) *Tetraprioniodus elegans* Moskalenko: (2) Specimen 87180/188-17, side view, ×40, (8) Specimen 87180/165-1, side view, ×30, the same locality and stratigraphic position; (3, 5, 22, 23) *Aphelognathus pyramidalis* (Branson, Mehl et Branson): (3) Specimen 87180/193-2, S_c-element, frontal view, ×55, (5) Specimen 90190/235-18, S_b-element, back view, ×50, (22) Specimen 90190/250-3, S_b-elements, back view, ×60, (23) Specimen 87180/193-14, P_b-element, side view, ×50, the same locality and stratigraphic position; (4) *Belodina brakhfogeli* Tarabukin sp. nov., Specimen 90190/235-19, side view, ×30, the same locality and stratigraphic position; (7, 9, 14) *Acanthocordylodus fidelis* Moskalenko: (7) Specimen 87180/193-6, side view, ×36, (9) Specimen 87180/193-5, side view, ×40, (14) Specimen 87180/193-3, side view, ×35, the same locality and stratigraphic position; (10, 20) *Panderodus* sp.: (10) Specimen 90190/228-1, side view, ×45, (20)) Specimen 90190/235-13, side view, ×24, the same locality and stratigraphic position; (12) *Distomodus kentuckyensis* Branson et Branson, Specimen 94369-15-1, side view, ×40, pipe Yubileinaya, Lower Silurian, Llandovery; (15) *Scandodus anceps* Moskalenko, Specimen 91168/185-18, side view, ×50, the same locality and stratigraphic position; (17) *Pseudobelodina? dispansa* (Branson et Mehl), Specimen 87180/165-11, side view, ×37, the same locality and stratigraphic position; (19) *Scabbarella altipes* Nowlan, Specimen 90190/228-2, side view, ×55, the same locality and stratigraphic position; (21) Gen. et sp. indet., Specimen 87180/193-13, side view, ×44, the same locality and stratigraphic position.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a narrow furrow located closer to the posterior edge, subparallel to the anterior edge, and gradually converging upward with the side. The posterior edge bears 5–6 closely spaced large denticles with rounded or, sometimes, acute margins; the latter are located above the posterior basal outgrowth. The main cusp is pointed.

Comparison. The species differs from the close form *Belodina confluens* Sweet because of a very wide cusp and large high posterior basal outgrowth isolated from the latter.

Notes. Small specimens are very similar to *Belodina confluens* Sweet but having slightly different square outlines.

Distribution: right bank of the Markha River, Siberian platform, Upper Ordovician, Ashgillian Stage, Bur Horizon, Delingda Formation.

Material: seven specimens of good to sufficient preservation from Well 90190 (depth of 235 m) drilled at the Pravoberezhnyi site in the upper reaches of the Markha River, Siberian platform.

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Reviewer A.S. Alekseev

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